GRAZING IN FUTURE MULTI-SCAPES: FROM THOUGHTSCAPES TO LANDSCAPES, CREATING HEALTH FROM THE GROUND UP

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GRAZING IN FUTURE MULTI-SCAPES: FROM THOUGHTSCAPES TO LANDSCAPES, CREATING HEALTH FROM THE GROUND UP

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Table of Contents

08 ***Editorial: Grazing in Future Multi-Scapes: From Thoughtscapes to Landscapes, Creating Health From the Ground Up***
Pablo Gregorini, Iain J. Gordon, Carol Kerven and Frederic D. Provenza

THOUGHTSCAPES

13 ***We Are the Earth and the Earth Is Us: How Palates Link Foodscapes, Landscapes, Heartscapes, and Thoughtscapes***
Frederick D. Provenza, Cindi Anderson and Pablo Gregorini

29 ***Pastoral Agriculture in the Post-industrial Age: Building Functional Integrity and Realising Potential***
Christopher J. K. Perley

40 ***Grazing Into the Anthropocene*** or ***Back to the Future?***
Roy H. Behnke

60 ***Livestock in Evolving Foodscapes and Thoughtscapes***
Frédéric Leroy, Adele H. Hite and Pablo Gregorini

SOCIALSCAPES

75 ***Understanding Alignments and Mis-Alignments of Values to Better Craft Institutions in the Pastoral Drylands***
Jane Addison, Colin Brown, Chris R. Pavey, Enkh-Orchlon Lkhagvadorj, Duinkherjav Bukhbat and Lkhagvadorj Dorjburegdaa

85 ***Controversies and Common Ground in Wild and Domestic Fine Fiber Production in Argentina***
Julieta von Thungen, Elisa Martin and Maria Rosa Lanari

96 ***The Role of Community Cooperative Institutions in Building Rural–Urban Linkages Under Urbanization of Pastoral Regions in China***
Gongbuzeren, Li Wenjun and Lai Yupei

105 ***The Future of Transhumants' Sustainable Resource Use in Bhutan: Pressures and Policies***
Kuenga Namgay, Joanne E. Millar and Rosemary S. Black

118 ***Pastoralism at Scale on the Kazakh Rangelands: From Clans to Workers to Ranchers***
Carol Kerven, Sarah Robinson and Roy Behnke

139 ***Mobilizing Ecological Processes for Herbivore Production: Farmers and Researchers Learning Together***
Bertrand Dumont, Pablo Modernel, Marc Benoit, Andrea Ruggia, Pablo Soca, Sylvain Dernat, Hervé Tournadre, Santiago Dogliotti and Walter A.H. Rossing

154 ***Pursuing Plurality: Exploring the Synergies and Challenges of Knowledge Co-production in Multifunctional Landscape Design***
Ritodhi Chakraborty, Sadeepa Jayathunga, Hirini Paerangi Matunga, Shannon Davis, Lizzie Matunga, James Eggers and Pablo Gregorini

175 ***One Place Doesn't Fit All: Improving the Effectiveness of Sustainability Standards by Accounting for Place***
Kevin E. Jablonski, Jasmine A. Dillon, James W. Hale, Becca B. R. Jablonski and Michael S. Carolan

185 ***With Power Comes Responsibility – A Rangelands Perspective on Forest Landscape Restoration***
Susanne Vetter

LANDSCAPES

195 ***Rangeland Ecosystem Service Markets: Panacea or Wicked Problem?***
Leslie M. Roche, Tina L. Saitone and Kenneth W. Tate

207 ***Grazing in California's Mediterranean Multi-Firescapes***
Lynn Huntsinger and Sheila Barry

229 ***Livestock Mobility Through Integrated Beef Production-Scapes Supports Rangeland Livestock Production and Conservation***
Sheila Barry

250 ***Management of Grazed Landscapes to Increase Soil Carbon Stocks in Temperate, Dryland Grasslands***
David Whitehead

257 ***Toward Specialized or Integrated Systems in Northwest Europe: On-Farm Eco-Efficiency of Dairy Farming in Germany***
Thorsten Reinsch, Cecilia Loza, Carsten Stefan Malisch, Iris Vogeler, Christof Kluß, Ralf Loges and Friedhelm Taube

277 ***Building the GLENCOE Platform -Grasslands LENding eConomic and ecOsystems sErvices***
Thais Devincenzi, Martín Jaurena, Martín Durante, Jean Víctor Savian, Gabriel Ciappesoni, Elly Ana Navajas, Veronica Ciganda, Fernando Alfredo Lattanzi and José Paruelo

281 ***Pasture-Based Dairy Systems in Temperate Lowlands: Challenges and Opportunities for the Future***
Luc Delaby, John A. Finn, Guylain Grange and Brendan Horan

294 ***Native Grasslands at the Core: A New Paradigm of Intensification for the Campos of Southern South America to Increase Economic and Environmental Sustainability***
Martín Jaurena, Martín Durante, Thais Devincenzi, Jean V. Savian, Diego Bendersky, Fernanda G. Moojen, Marcelo Pereira, Pablo Soca, Fernando L. F. Quadros, Rafael Pizzio, Carlos Nabinger, Paulo C. F. Carvalho and Fernando A. Lattanzi

309 ***Vegetation Options for Increasing Resilience in Pastoral Hill Country***
Katherine Tozer, Grant Douglas, Mike Dodd and Karin Müller

331 ***Reconnecting Grazing Livestock to Crop Landscapes: Reversing Specialization Trends to Restore Landscape Multifunctionality***
Paulo César de Faccio Carvalho, Pedro Arthur de Albuquerque Nunes, Arthur Pontes-Prates, Leonardo Silvestri Szymczak, William de Souza Filho, Fernanda Gomes Moojen and Gilles Lemaire

342 ***Beyond CO_2: Multiple Ecosystem Services From Ecologically Intensive Grazing Landscapes of South America***
Pablo Tittonell

353 ***Savannah Phenological Dynamics Reveal Spatio-Temporal Landscape Heterogeneity in Karamoja Sub-region, Uganda***
Anthony Egeru, John Paul Magaya, Derick Ansyijar Kuule, Aggrey Siya, Anthony Gidudu, Bernard Barasa and Jjumba Justine Namaalwa

FOOD AND HEALTHSCAPES

373 ***Review: Impact of Food and Climate Change on Pastoral Industries***
Md E. Uddin and Ermias Kebreab

386 ***Animal Welfare in Extensive Production Systems Is Still an Area of Concern***
Déborah Temple and Xavier Manteca

404 ***Ecological Implications of Plant Secondary Metabolites - Phytochemical Diversity Can Enhance Agricultural Sustainability***
Andrea K. Clemensen, Frederick D. Provenza, John R. Hendrickson and Michael A. Grusak

413 ***Health-Promoting Phytonutrients Are Higher in Grass-Fed Meat and Milk***
Stephan van Vliet, Frederick D. Provenza and Scott L. Kronberg

WILDSCAPES

433 ***Domestic Livestock and Rewilding: Are They Mutually Exclusive?***
Iain J. Gordon, Adrian D. Manning, Laetitia M. Navarro and Julia Rouet-Leduc

447 ***Goat Grazing for Restoring, Managing, and Conserving "Satoyama", a Unique Socio-Ecological Production Landscape***
Masato Yayota and Kazuya Doi

453 ***Managing Rangelands Without Herding? Insights From Africa and Beyond***
Eva Schlecht, Matthew D. Turner, Christian G. Hülsebusch and Andreas Buerkert

466 ***The Shrinking Resource Base of Pastoralism: Saami Reindeer Husbandry in a Climate of Change***
Nicholas J. C. Tyler, Inger Hanssen-Bauer, Eirik J. Førland and Christian Nellemann

512 ***Quantitative Spatial Ecology to Promote Human-Wildlife Coexistence: A Tool for Integrated Landscape Management***
Daniel Fortin, Christopher F. Brooke, Patricia Lamirande, Hervé Fritz, Philip D. McLoughlin and Olivier Pays

525 ***Conservation Policies, Eco-Tourism, and End of Pastoralism in Indian Himalaya?***
Rashmi Singh, Rishi Kumar Sharma, Tsering Uden Bhutia, Kinzong Bhutia and Suresh Babu

DESIGN AND INNOVATION

536 ***Designing Diverse Agricultural Pastures for Improving Ruminant Production Systems***
Roberto A. Distel, José I. Arroquy, Sebastián Lagrange and Juan J. Villalba

554 ***Urban Foodscapes and Greenspace Design: Integrating Grazing Landscapes Within Multi-Use Urban Parks***
Shannon Davis

565 ***Back to Nature With Fenceless Farms—Technology Opportunities to Reconnect People and Food***
David L. Swain and Stuart M. Charters

576 ***Using Research to Support Transformative Impacts on Complex, "Wicked Problems" With Pastoral Peoples in Rangelands***
Robin S. Reid, María E. Fernández-Giménez, Hailey Wilmer, Tomas Pickering, Karim-Aly S. Kassam, Apin Yasin, Lauren M. Porensky, Justin D. Derner, David Nkedianye, Chantsallkham Jamsranjav, Khishigbayar Jamiyansharav, Tungalag Ulambayar, Elisa Oteros-Rozas, Federica Ravera, Umed Bulbulshoev, Daler S. Kaziev and Corrine N. Knapp

600 ***Multi-Scape Interventions to Match Spatial Scales of Demand and Supply of Ecosystem Services***
Emilio A. Laca

612 ***Integrating Digital Technologies to Aid Grassland Productivity and Sustainability***
David R. Stevens, Bryan R. Thompson, Patricia Johnson, Brendon Welten, Esther Meenken and Jeremy Bryant

622 ***Opportunities to Apply Precision Livestock Management on Rangelands***
Derek W. Bailey, Mark G. Trotter, Colin Tobin and Milt G. Thomas

635 ***Red Chittagong Cattle: An Indigenous Breed to Help Tackle the Challenges of Modern Animal Production Systems***
Nani Gopal Das, Mohammed R. Islam, Nathu Ram Sarker, Md. Abdul Jalil and Cameron E. F. Clark

644 ***Individual Monitoring of Behavior to Enhance Productivity and Welfare of Animals in Small-Scale Intensive Cattle Grazing Systems***
Hiroki Anzai and Masahiko Hirata

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EDITORIAL
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Editorial: Grazing in Future Multi-Scapes: From Thoughtscapes to Landscapes, Creating Health From the Ground Up

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Editorial on the Research Topics

Grazing in Future Multi-Scapes: From Thoughtscapes to Landscapes, Creating Health From the Ground Up

More than half the land surface of the Earth is used for grazing (United Nations General Assembly, 2022), with Asia at 36% and Africa at 30% of the total. About 91% of global grass- and range-lands are unfenced with few boundaries and limited crop farming (Reid et al., 2014). The remaining grass- and range-lands are privately owned and used, with 13% in North America, 10% in Australia and New Zealand, 8% in South America, and 3% in Europe; all with a mix of more intensive grazing and cultivated land. No wonder why across the world's landscapes, grazing and browsing herbivores—both wild and livestock—(be they within a spatial and temporal pastoral context, whether they naturally graze or are grazed by farmers, ranchers, shepherds, and nomadic peoples—all termed pastoralists), fulfill essential roles in driving the composition, structure, and dynamics of pastoral ecosystem. The provision of ecosystem services, including social, economic, and cultural benefits to families, farms, and communities, is accordingly impacted (Gregorini, 2015).

The term "pastoralism" may imply different types of livestock production in different countries. In Australia, for instance, pastoralism refers to ranchers with private rights over fenced properties, whereas pastoralism in Kenya commonly excludes fenced properties and refers to livestock producers operating on collectively owned and unfenced ranges. In Kenya as in many other countries e.g., Argentina (Wane et al., 2020), Botswana (De Ridder and Wagenaar, 1986), or the USA (Huntsinger et al., 2010), in some academic writing (Homewood, 2018), and the development literature (CELEP, 2021), ranchers would not be considered the same as pastoralists. In short, there is no generally accepted definition of pastoralism.

In this Research Topic of papers, we define "pastoralism" as the extensive production of domestic livestock, primarily dependent on the grazing of natural forages (see **Supplementary Material** for further discussion and examples). This definition of pastoralism excludes intensive livestock farming which is heavily dependent on feed supplements or cultivated pastures. As will become clear below, this definition of pastoralism includes people that both Australians and Kenyans would call pastoralists.

Pastoralists are found from the Arctic to the Kalahari Desert, from the Andes to Tibet, grazing reindeer and yaks in the north to alpaca and llamas in the south, to cattle, goats, sheep, and other species in between, while sharing the land-scapes with a wide variety of wild grazers and browsers, from kangaroos to elephants to bison (Reid et al., 2008).

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In many cases, grazing of domesticated and/or semi-domesticated livestock, often focused on the objectives of maximizing animal production and/or profit alone, has transformed landscapes in ways that diminished biodiversity, reduced water and air quality, accelerated loss of soil and plant biomass, and displaced indigenous livestock breeds and peoples. Where this has happened, these degenerative transformations have broken the integration of land, water, air, health, society, and culture, jeopardizing present and future ecosystem and societal services (Gregorini and Maxwell, 2020). As a consequence of these myopic grazing practices and thereby "land-scape" degradation, many land-users, policymakers and societies are calling for alternative approaches to the management of pastoral systems, keeping the good whilst throwing out the bad; diversified, adaptive and integrative agro-ecological and food-pastoral-systems that operate across multiple scales and "scapes" (e.g., thought-, social-, land-, food-, health-, and wild-scapes). To achieve these objectives requires a paradigm shift in livestock production systems embedded in a greater level of consciousness. This would be derived, initially from our perceptions about how these systems provide wealth, health, and wellbeing. The purpose of this Research Topic and book is to encourage people to reconceptualise models and practices of grazing and pastoral systems in continually evolving multiscapes. We provide a Research Topic of papers framed in different—but not necessarily separated—scapes (thought, social, land, food, wild, health and policy) that we hope will cultivate a shift in understanding and thinking, leading to new and revived choices and thereby a paradigm change as originally proposed by Schiere et al. (2012) in a seminal work on "Dynamics in farming systems: of changes and choices".

Building on Aldrich's (1966) definition of landscape—a view of a space or scenery from a specific perspective—here we refer to thoughtscapes as a geography of minds' perception and how we locate ourselves and participate in such a perception from our individual point of view and emotions. Any landscape will be perceived and felt differentially depending on who is thinking about, has experienced or is experiencing it, as well as their expectations of that -scape—their perception of its uses, their priorities and cultural values, as well as on how people function within a landscape and how the landscape impacts upon them.

Several papers in this Research Topic and book offer food for thought about thoughtscapes. For example, historically, to manage the supply of animal protein, our hunter-gatherer ancestors domesticated and confined wild animals within enclosures, one of the earliest forms of agricultural -scapes. Swain and Charters discuss how the modern invention of fences created a culture of control and ownership in some Euro-American and Australasian grass- and range-lands, and they explore opportunities for fenceless landscapes. Contemporary challenges, as a consequence of the increased industrialized view of agriculture and food, increased meat supply, and the disconnect of most people from the food chain, are fuelling societal anxieties about the roles of agriculture and meat in human foodscapes and healthscapes. Leroy et al. (2022) contend that these issues may enhance "anti-livestock and or animal as food source" ideologies that could lead to more holistic, ethical and sustainable human-animal-land interactions. As Beck and Gregorini point out, pastoral production systems, based on higher external inputs, face societal pressure to reduce environmental impacts, enhance animal welfare (also see Temple and Manteca), promote the integrity of meat and dairy products, and maintain profitability. They show how providing livestock with functionally diverse feeding contexts, that better meet individual needs for nutrients, pharmaceuticals, and prophylactics, can improve their health and wellbeing by enhancing hedonics and eudemonics. van Vliet et al. show that as the phytochemical diversity (see Beck and Gregorini; Distel et al.) of the diets of livestock increases, so do health-promoting phytochemicals and biochemicals in the meat and dairy products humans consume. Moreover, roots exude some phytochemicals thus influence soil macrobiota and nutrient dynamics. In turn, when livestock consume phytochemically rich plants, they also excrete some of those compounds, enhancing or adding to the benefits coming from those plants' effects *per se* (Clemensen et al.). In other words, plant diversity enhances health from the ground up. Enhanced animal eudemonic and hedonic wellbeing, coupled with better health, suggests that phytochemically functional dietary diversity will improve not only animal welfare, but also wellbeing (mental state and health) of "them and us" (Beck and Gregorini, 2020). That, in turn, can enhance the eating experience and thus hedonic wellbeing (i.e. "healthy" pleasure) of the consumer, knowing that – in fact – such livestock products are healthier and in tune with the land and animal integrity. All of that could shift the directions of generic (one size fits all) "agri-business" models based on industrial inputs to more holistic ways of viewing health from the ground up.

Jaurena et al. use trial and case studies to show how managed grazing on private ranches can reduce financial risks and increase the profitability and environmental sustainability of livestock production on native grasslands (also see Dumont et al.). Growing interest in incentivizing sustainable agricultural practices, to enhance the provision of ecosystem services, is supported by a large network of voluntary production standards in high income countries that offer farmers and ranchers increased value for their products in support of "better" environmental sustainability. As Jablonski et al. point out, to be effective these standards must be credible, broadly recognizable, and generalizable, yet agriculture is place-based and varies considerably – it is not generic, even within a specific region, due to uniquely complex biophysical, socio-cultural, and management-based factors. This contradiction between the placeless generality of standards and the place-based nature of agriculture renders most sustainability standards ineffectual. Coping solutions and tools are emerging though, as shown by Laca, who provides a conceptual and quantitative basis to the spatial and temporal distribution of ecosystem services relative to demand, as the original focus of ecosystem services shifts to matching placed-based supply with demand. And at a greater "level", as discussed by Perley, we need to consider how modern emerging alternatives/models shift the uniform/generic "economies of scale" of industrialism to potential "economies of scope", created locally in communities as systems self-organize.

Provenza et al. use linkages among food-, land-, heart-, and thought-scapes to discuss transformations of consciousness needed to appreciate life on earth as a community to which we belong, rather than as a commodity that belongs to us. Therefore, alternative thoughtscapes should encourage pastoral ranching models that move away from the degenerative, one-dimensional, and myopic concept of industrial pastoralism (Leroy et al., 2022). In this industrial model, animals are perceived solely as a resource, existing in isolation from their wider landscape and societal functions (e.g., provide fuel, fertilizer, transport, and haulage services; offer individual and collective insurance; embody/establish social relationships through their exchange in marriage or clientage; and, have cultural and religious significance). Taking a more holistic view of industrial pastoralism will enable individual thoughtscapes to become collective ones of and in modern societies, in relation to the functions of pastoral communities and industries.... i.e. new ethical social-scapes in the making (Gregorini and Maxwell, 2020).

The papers focussing on social-scapes add more dimensions, presenting a variety of pastoralism cases—mobile, sedentary, and in-between, in high income countries:—New Zealand, United States, Australia, Argentina, Spain, Kazakhstan, China and South Africa -and nations—from low to middle- Mongolia, Tajikistan, Bhutan, Kenya, and Tanzania. In all these settings, people make a living from raising livestock on pastures in a socio-cultural context, not only in a specific environment or political-economic locus. The influence of social, cultural, and indigenous (Chakraborty et al.) values on land management is overlooked at great cost. Partnerships between natural and social scientists increasingly seek to understand pastoralism and rangelands by collaborating across formal disciplines and extending the "sometimes rigid and virtuous" boundaries of their research to work with many different parts of society. Transdisciplinary science, therefore, leads to growing awareness of alternative epistemologies among groups, i.e., how knowledge is acquired, filtered, enculturated, rationalized, shared and applied to the environment we work on and the landscapes we all inhabit.

Rangelands are observed differently by the state as enacted through *de facto* or implicit policies; by the managers endeavoring to implement state policies; by scientists positioned outside state management (though often reliant on state funding), and ultimately by the peoples whose livelihoods are in one way or another dependent on the rangelands. Priorities can be misaligned between these groups: "re-imagining of grazed landscapes must recognize that current pastoralists have their own visions of what pastoralism does, can and should provide to both themselves and society at large" (Addison et al.). Large-scale internationally funded programmes may contradict or compromise, not to mention negate, pastoral interests, as in afforestation of drylands and grassy biomes in Africa (Vetter). National programmes to intensify or de-intensify livestock production are altering peoples' "grazing landscape and socialscape" among transhumants in Bhutan (Namgay et al.) or Sami herders in the Arctic (Tyler et al.). Studies on pastoralists in Argentina also note that "Top down or bottom-up experiences hold distinct epistemological and research consequences and they affect rural livelihoods in various ways" (von Thungen et al.). Negotiating these viewpoints requires mediation and objectivity (Addison et al.; Reid et al.). Fundamentally, bridging these views entails collaboration between the disparate parties, for example, ranchers and conservationists, or indigenous peoples and scientists (Chakraborty et al.). There is a strong impetus to address complex problems "because local pastoral voices (and sometimes science) still have little impact on decision-making in the governmental and private sectors" (Reid et al.). Regulations can have profound and undesirable impacts, as in the Californian wildfires since "indigenous long-term knowledge of ecology was not used in developing policies for forest and land management" (Hunsinger and Barry). The weight of western science lies heavily on the peoples on the range- and grass- landscapes, including those in the great socialist experiments of the USSR and P.R. China (Kerven et al.; Zeren et al., 2021). Over time we discern that pastoralists in these and previously mentioned landscapes are not stubbornly conservative or passive in the face of change, but can and do adapt innovatively.

Ko au te whenua, ko te whenua ko au. I am the land, the land is me. We are the earth and the earth is us... (Provenza et al.). Landscapes are multi-dimensional domains we must protect and nurture to restore our collective health and wellbeing. Within landscapes are the foodscapes that nourish humans and herbivores. Foodscapes management and dietary perceptions dictate actions and reactions of herbivores (Distel et al.; Temple and Manteca) and us (Leroy et al.). Foodscapes management and dietary perceptions are changing as developed countries grapple with food-related diseases and obesity, and developing countries battle regional famines, malnutrition, and starvation, while the whole world deals with impacts of biohazards such as the coronavirus and climate change. In some richer societies, there are demands for health-scapes and nutraceutical food-scapes and, paradoxically, there is a movement away from animal products in pursuit of healthier lives, even though animal products are the best sources of some nutrients essential for human health (Leroy et al., 2022; van Vliet et al.). Meanwhile, as populations grow and incomes rise in poorer countries, demand for animal products is increasing. This raises the question of how best to react to these, apparently contradictory trends, demands on "the land". The question is: Should sustainability assessments to inform the grazing landscapes look beyond greenhouse gas emissions to simultaneously embrace other social and environmental criteria? As concluded by Tittonell "truly sustainable, multifunctional grazing landscapes requires expanding our thinking and narratives beyond narrow discussions informed by greenhouse gas emissions or carbon footprint assessments."

Although the peoples who rely on grazing-lands for their livelihoods often have few alternatives, there are encouraging new and revived research approaches to grazing management (e.g. related to carbon sequestration; Uddin and Kebreab; Whitehead). For instance, de Faccio Carvalho et al. discuss how to restore landscape multifunctionality by creating more biodiverse mixed farming systems that integrate livestock grazing into cropping landscapes to reverse industrial specialization and consider multiple demands to farming landscapes. Or even, as argued by Davis, grazing lands for sheep and beef production can be designed within a public urban park alongside other park uses as well. Moreover, recognizing and rewarding herders and grazing for multiple ecosystem services would make herding less strenuous and politically, socially, and financially more secure (Schlecht et al.). Relationships and tools are emerging, and we can discern some better options for the future of our land under grazing, though compromises and trade-offs will be necessary.

While native species of animals (wildscapes) and indigenous peoples have been displaced from many of their lands by monotonic pastoralism, multifunctional pastoral systems can be designed to achieve dynamic multi-scapes that embed local breeds, native species of plants and animals and indigenous peoples into broader society. Here the papers focussing on wildscapes add even more grist to the mill. Landscapes range from highly intensively used for agricultural commodity production to wilderness areas with little or no recent human impacts. Whilst the latter are rare (Plumptre et al., 2021), a range of landscapes contain attributes of natural composition, structure, and processes (wildscapes), many of which have been shaped by humans and their livestock over millennia (Behnke). In the second decade of the 21st Century, pastoral lands are being abandoned, particularly in the developed world, and this trend may increase with pressures placed on livestock from issues such as greenhouse gas emissions and a changing acceptance of meat as a food in the western world (Leroy et al.). These trends yield benefits through the ecosystem services wildscapes can provide, although these need to be managed and properly incentivised for land managers, as increased rates of extinction of wildlife populations, in association with human activity, are the hallmark of the Anthropocene (Fortin et al.). The loss of grazing by large herbivores, across many wildscapes, poses risks of increased wildfires (Huntsinger and Barry), and invasive species. For these reasons pastoral wildscapes require some form of management intervention (Gordon et al.). For example, Fortin et al. present a spatial ecology tool to promote human-wildlife coexistence for integrated landscape management. Indigenous peoples should participate in shaping and delivering these management interventions (Singh et al.; Tyler et al.)—following the principles of adaptive management. A typical approach is revisiting old stories—many indigenous peoples have been using these management practices and tools for generations, including fire and traditional breeds of livestock (Gordon et al.). But society must factor in how to make this economically viable for people who provide these environmental services (Roche et al.).

To conclude and encourage the reader to delve into this Research Topic and book—pastoral lands are in transition, and this brings with it challenges as well as opportunities. Some governments are focusing on curbing the negative externalities of farming and livestock production within national policies, whilst others will not tackle, or are complicit in, problems of insecurity of rangeland tenure, land grabbing and conversion to non-pastoral activities such as irrigated commercial farming, urban development, or mining (Oakland Institute, 2022). Such transitions, in many cases, have undermined the autonomy of pastoralists. The lack of autonomy further threatens our pastoral landscapes, through the rise of competing agendas when addressing the complicated social-ecological relationships; for example, environmental compliance, biodiversity conservation, livelihood security, climate change mitigation/adaptation, animal welfare, and sustainable consumption. While attempts at relational engagements are often assembled through political, intellectual, and institutional hierarchies, in truth it often seems that the divisions among these different interest groups are only growing ever wider. Our purpose is to encourage people to reconceptualise models and practices of pastoralists in continually evolving multiscapes. Unfortunately, the process of deciding the future of pastoral production systems is often exclusionary, failing to capitalize on the synergies that could be created across the spectrum of stakeholders' views, needs and feelings about different -scapes. The concept of "multiscapes" is a unifying view for learning how pastoral lands were, are and can be, under newer functions and paradigm shifts. This is the heart of our thought-scapes as expressed in this body of work.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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SUPPLEMENTARY MATERIAL

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We Are the Earth and the Earth Is Us: How Palates Link Foodscapes, Landscapes, Heartscapes, and Thoughtscapes

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Humans are participating in the sixth mass extinction, and for the first time in 200,000 years, our species may be on the brink of extinction. We are facing the greatest challenges we have ever encountered, namely how to nourish eight billion people in the face of changing climates ecologically, diminish disparity between the haves and the have-nots economically, and ease xenophobia, fear, and hatred socially? Historically, our tribal nature served us well, but the costs of tribalism are now far too great for one people inhabiting one tiny orb. If we hope to survive, we must mend the divides that isolate us from one another and the communities we inhabit. While not doing so could be our undoing, doing so could transform our collective consciousness into one that respects, nourishes, and embraces our interdependence with life on Earth. At a basic level, we can cultivate life by using nature as a model for how to produce and consume food; by decreasing our dependence on fossil fuels for energy to grow, process, and transport food; and by transcending persistent battles over one-size-fits-all plant- or animal-based diets. If we learn to do so in ways that nourish life, we may awaken individually and collectively to the wisdom of the Maori proverb *Ko au te whenua. Ko te whenua Ko au: I am the land. The land is me*. In this paper, we use "scapes" —foodscapes, landscapes, heartscapes, and thoughtscapes—as unifying themes to discuss our linkages with communities. We begin by considering how palates link animals with foodscapes. Next, we address how palates link foodscapes with landscapes. We then consider how, through our reverence for life, heartscapes link palates with foodscapes and landscapes. We conclude with transformations of thoughtscapes needed to appreciate life on Earth as a community to which we belong, rather than as a commodity that belongs to us.

Keywords: vegetarian and non-vegetarian diets, plant diversity and abundance, animal welfare, climate change, fossil fuels, farming and wildlife, ecological economic benefits, transformation of consciousness and behavior

INTRODUCTION

For nearly 200,000 years, *Homo sapiens* gathered plants and hunted animals for nourishment. While our ancestors altered landscapes with fire and agriculture, modern hominids have changed landscapes in unprecedented ways. We have gone from a species reliant on nature for food, medicine, clothing, and shelter to one that scarcely knows nature exists outside of movies, local and national parks. Most people cannot identify the plants that grow in vegetable, herbal, or medicinal gardens, let alone the wild plants and animals in their communities, though their ancestors would have revered them and known their many roles in nourishing our species. In a vivid illustration of this mass delusion, some societies are now in the midst of convincing themselves that plant-based faux meat is better than the real thing and that nature is a feeble-minded nitwit compared to the "time-tested wisdom" of Silicon Valley technologies. People in "developed" societies have lost the wisdom that comes from living closely with nature.

Aldo Leopold began *A Sand County Almanac* with this statement (Leopold, 1949): "There are some who can live without wild things, and some who cannot. These essays are the delights and dilemmas of one who cannot." His book was a heart-felt account of how our growing detachment from nature was wreaking havoc on nature's communities. Yet, despite his eloquent pleas, the changes that fossil-fuel based human societies have fashioned since his death, nearly 75 years ago, are breath-taking. From the plundering of plants, animals, and Indigenous peoples during the era of nineteenth-century manifest destiny in the U.S. to current times, humans have participated in the extinction of many of the plants and animals that make this planet habitable (Kolbert, 2014). We are now being consumed by changes we wrought and consequences we did not foresee. Leopold concludes: "We abuse land because we regard it as a commodity belonging to us. When we see land as a community to which we belong, we may begin to use it with love and respect."

Changing climates, massive declines in populations of plants and animals, economic and social inequities are all reminders of our lack of compassion for life on Earth. We can come to love and respect life by transforming our utilitarian views of plants and animals merely as sources of food to a reverence for their wide-ranging ecological, economic, and social meanings and values. In this paper, we use "scapes"—foodscapes, landscapes, heartscapes, and thoughtscapes—as unifying themes to discuss how palates link people with land. We begin by considering how palates link animals with foodscape; we then address the links between foodscapes and landscapes; next we consider how, through a reverence for life, heartscapes link palates with foodscapes and landscapes; we conclude with the transformations of thoughtscapes required to appreciate land as a community to which we belong, rather than as a commodity belonging to us.

We relate our reflections on "scapes" to the seven chakras or energy centers of the body (**Figure 1**). When foodscapes, landscapes, heartscapes, and thoughtscapes are linked and aligned, using the imagery of the chakras, so too is the human linked and aligned with the community of Earth. Life cannot exist without the nourishment of foodscapes (root chakra). Nor can life persist without reproducing itself (sacral chakra). To thrive, creatures create relationships with the landscapes they inhabit (which links the root, sacral, and solar plexus chakras). Our creative capacity to nurture plants, animals, and people depends on our ability to give and receive love (the heart chakra, which is the conduit from the root, sacral, and solar plexus to the throat, third eye, and crown chakras). When we are well-grounded in the other six chakras, we speak clearly and truthfully (throat chakra). That ability comes from awareness gained *via* the non-cognitive, intuitive, inclusive facets of being, as opposed to the cognitive, rational, analytical details of life (third eye chakra). Awareness that "I am" is naught, that all knowledge and being—including what I call "my" self—is illusory occurs when consciousness is liberated to its true state (crown chakra) prior to the time (our birth) when we each begin to identify with "my" self.

PALATES LINK ANIMALS WITH FOODSCAPES

Palates link animals with foodscapes—those parts of landscapes animals use to nourish and self-medicate—through three interrelated processes (Provenza et al., 2015, 2019; Provenza, 2018; **Figure 1**, root chakra). First, animals must have access to a variety of wholesome foods. The more they are restricted—for instance to a feedlot ration for livestock or ultra-processed foods for people—the less they can sustain health. Second, mother is a transgenerational link to foodscapes. Her knowledge—of what and what not to eat and where and where not to go to forage—is essential for helping her offspring get a start in life. Her influence begins in the womb (through flavors in her amniotic fluid), and continues at birth (through flavors in her milk) and when her offspring begin to forage (as a model for what and what not to eat). Third, liking for food is mediated by feedback from cells and organ systems, including the microbiome, in response to nutritional and medicinal needs that are met by nutrients (energy, protein, minerals, and vitamins) and the thousands of compounds plants produce (phenols, terpenes, and alkaloids).

Foodscapes with complex mixtures of grasses, forbs, shrubs, and trees are nutrition centers and pharmacies with vast arrays of phytochemicals (Provenza, 2018). Nothing is more important for health than foodscapes with a variety of foods for herbivores, omnivores, and carnivores. For herbivores, the bulk of any one meal is typically comprised of 3–5 plants, but they often eat small amounts of 50–75 plants during the day. Historically, we did not appreciate that the nutritional and pharmacological properties of these minor components of the diet—best eaten in small doses—enable health (Provenza, 2018). Compared with pastures that lack plant diversity or monotonous feedlot diets, animal welfare and well-being—including nutritional, physiological (blood parameters indicative of health), and immunological (immune function) status—all improve when livestock forage on diverse mixtures of phytochemically rich plants (Villalba et al., 2017, 2019; Beck and Gregorini, 2020; Lagrange et al., 2020; Redoy et al., 2020). That is why livestock foraging on phytochemically rich foodscapes do not require antiparasitic drugs or antibiotics and they also have low levels of morbidity and

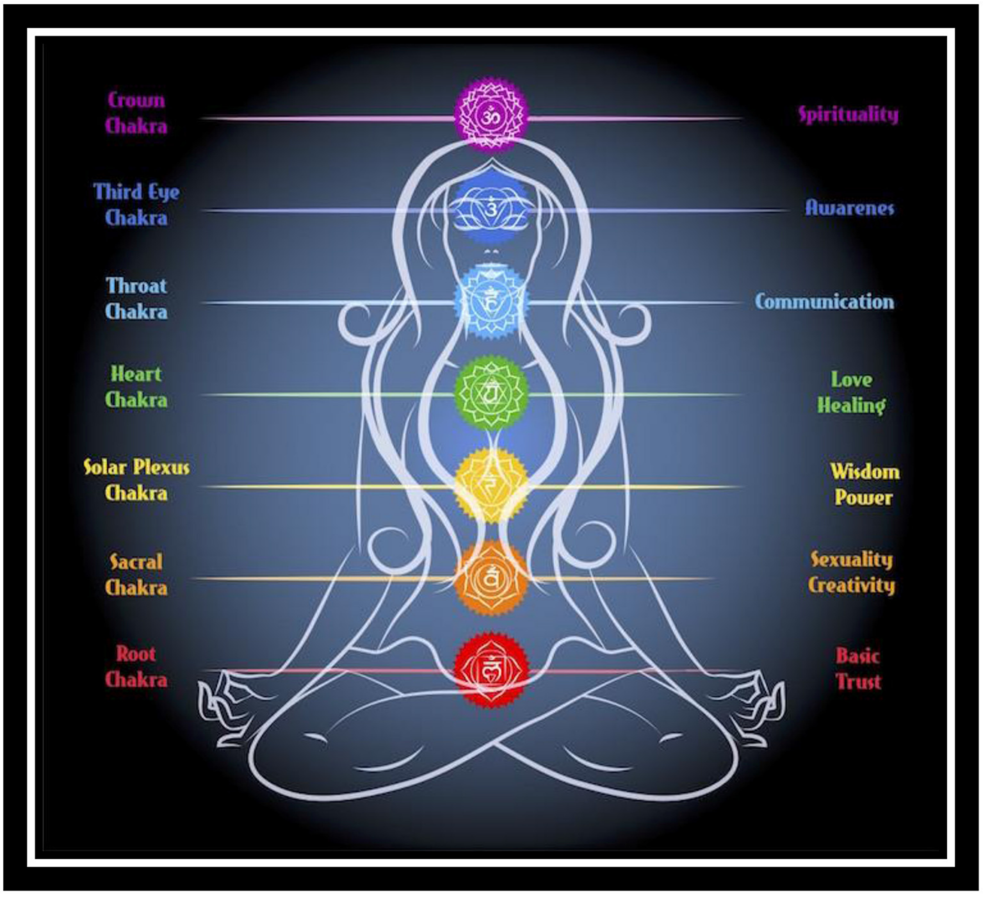

FIGURE 1 | We explore how palates link humans with foodscapes, landscapes, heartscapes, and thoughtscapes. Our reflections have parallels with the seven chakras or energy centers of the body. The root chakra is the foundation, akin to foodscapes nourishing humans. The sacral chakra, which governs sexual energy and creativity, links foodscapes with activities in landscapes. The solar plexus chakra, our ability to feel in control of our life, reflects our relationships with the landscapes we inhabit. The heart chakra is the bridge between the lower chakras (associated with physicality) and the upper chakras (associated with spirituality). This chakra reflects our ability to give and receive love, the basis for our capacity to nurture plants, animals, and people. The throat chakra gives voice to the heart chakra: when we are grounded in the other six chakras, we express ourselves clearly and truthfully. The third eye chakra is awareness gained through the non-cognitive, intuitive, inclusive facets of our being, as opposed simply to the cognitive, rational, analytical details of existence. The crown chakra is transcendent of "I am's" — and all illusions of duality. It is absolute awareness that "I am" is naught, all knowledge—including what I call "my" self—is liquidated and consciousness is liberated to its true state prior to any identification with physical form and function.

mortality compared with animals forced to forage on pastures with few plant species or in feedlots (Provenza et al., 2019).

In turn, human health is linked with the diets of livestock through the chemical features of the plants that livestock eat (Provenza et al., 2015; Gregorini et al., 2017). That includes not only energy, protein, minerals, and vitamins that plants contain, but the tens of thousands of other compounds that plants produce, collectively termed phytochemicals or the plant metabolome. This rich pool of compounds is increasingly recognized as responsible—as a complex whole—when trying to understand how plants promote health in herbivores or omnivorous humans who eat plants and meat (Nelson et al., 2017; Barabási et al., 2019). Through their many properties—that include anti-inflammatory, anti-microbial, anti-parasitic, and immunomodulatory effects—phytochemicals bolster health and protect livestock and humans against diseases and pathogens.

The benefits to humans of eating phytochemically/biochemically rich meat accrue as livestock assimilate some phytochemicals and convert others into metabolites that become muscle and fat, which become the phytochemicals/biochemicals that promote health (Provenza et al., 2019; Prache et al., 2020; van Vliet et al., 2021). That is similar to, but distinct from, the benefits realized by eating phytochemically rich herbs, spices, vegetables, and fruits (Tapsell et al., 2006). This expanded pool of compounds—phytochemicals and metabolites produced by animals from plants—should be considered in attempts to understand benefits to humans, such as damping oxidative stress and inflammation linked with cancer, cardiovascular disease, and metabolic syndrome.

The metabolic effects of eating meat from animals foraging on phytochemically rich diets are partially due to the ability of phytochemicals to curb inflammation (van Vliet et al., 2021). Eating meat from cattle raised on non-diverse pasture or grain-finished in feedlots does not have similar beneficial effects on inflammation (Arya et al., 2010; Gilmore et al., 2011). Low-grade systemic inflammation, characterized by elevated levels of cytokines (e.g., interleukin-6, tumor necrosis factor-alpha, and C-reactive protein), contributes to metabolic disease, type II diabetes, heart disease, cancer, and arthritis (Libby, 2007). Notably, cytokines respond within a meal (Holmer-Jensen et al., 2011), with increasing likelihood of developing diseases when meals that elevate inflammation become dietary habits (Esposito and Giugliano, 2006). Moderating inflammation through wholesome diets, however, can prevent or treat metabolic disease.

Most humans are omnivores who satisfy their needs for nourishment with a combination of animal and plant foods. While differences among individuals in form and function help to explain why some people can thrive on either animal- or plant-based diets (Williams, 1988), most people can best meet their needs with a combination of meat and plants. Animal and plant foods thus function symbiotically to nurture human health (van Vliet et al., 2021).

Compared with meat, plants more readily meet our needs for vitamin C and magnesium and plants are often higher than meats in folate, manganese, thiamin, potassium, and vitamin E (van Vliet et al., 2021). In addition to their many health-promoting properties, phytochemicals also antagonize deleterious effects of compounds found in cooked red meat, including heterocyclic amines, nitroso compounds, malondialdehyde, and advanced glycation end products (Provenza et al., 2019). These findings help explain why omnivorous diets rich in plants do not show links between red meat consumption and negative health outcomes often observed in population studies of people consuming a Standard American/Western Diet (Kappeler et al., 2013).

Relative to plants, meat provides all of the essential amino acids; minerals such as calcium, iron, selenium, zinc; vitamins A (retinol), B_{12} (adenosyl- and hydroxocobalamin), D (cholecalciferol), K2 (menaquinone-4); and long-chain polyunsaturated fatty acid including docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), which are most readily, or solely, obtained from meat (van Vliet et al., 2020, 2021). Eating a small amount (30 g) of dry beef can meet daily needs of a healthy 70-kg adult for taurine, carnosine, creatine, anserine, and 4-hydroxyproline, which improve metabolic, retinal, immunological, muscular, cartilage, neurological, and cardiovascular health (Wu, 2020). The value of meat for helping people meet various nutritional needs helps to explain why, even though vegetarians report a low desire to eat meat, their neural activity reveals a craving for meat (Giraldo et al., 2019). Their responses also highlight the discord between acquired beliefs about meat and inherent needs for nutrients contained in meat (Provenza, 2018).

Attempts to mimic meat with plant-based alternatives—using isolated plant proteins, fats, vitamins, and minerals—underestimate the nutritional complexity of whole foods, which contain tens of thousands of phytochemicals and biochemicals that promote health nutritionally and pharmacologically (Jacobs and Tapsell, 2007; Provenza, 2018; Barabási et al., 2019; van Vliet et al., 2021; https://foodb.ca/foods/FOOD00495). Moreover, while some proteins in plant-based meat alternatives have similar digestibilities to those in real meat, they are not converted as efficiently into muscle (van Vliet et al., 2015, 2018). Thus, compared with plants, people need to eat less meat to meet their needs for protein (Adesogan et al., 2019; van Vliet et al., 2021).

Eating meat from animals who eat phytochemically rich diets nourishes and satiates. In *Life in the Rocky Mountains*, Warren Angus Ferris recounts his adventures in the headwaters of the Missouri, Columbia, and Colorado Rivers from 1830 to 1835 (Ferris, 2012). Back then, roughly 60,000 bison fed on diverse mixes of plants and Ferris' crew fed on bison, as Indigenous people had done for ages. He notes bison in poor flesh were the worst diet imaginable, but as they became fat, no other meat could compare. "With it we require no seasoning; we boil, roast, or fry it, as we please, and live upon it solely, without bread or vegetables of any kind, and what seems most singular, we never tire of or disrelish it, which would be the case with almost any other meat."

Earth's health depends on diverse mixes of plants, which can be enhanced by managing grazing (IPCC, 2019). While many ways exist to do that (Teague et al., 2013), at the highest level of sophistication, a skilled herder is a "chef" who designs daily meal courses to improve the health of livestock and ecosystems (Meuret and Provenza, 2014, 2015). A flock in the hands of an "ecological doctor" can create healthy soil, plants, animals, and food for people in ways that enhance biodiversity, mitigate fires, and sustain local cultures—benefits not considered in life cycle analyses (Pilling et al., 2020). Those benefits matter as two-thirds of Earth's land mass, unsuitable for crops, is home to two billion people who depend on livestock for their livelihood (White, 2015). They can reduce the economic and social costs of livestock production, while boosting the quantity and quality of the foods they produce, through low-cost, non-fossil-fuel-intensive practices that include managing grazing, raising locally adapted animals, and eating meat and milk products (Provenza, 2008; Eisler et al., 2014; Varijakshapanicker et al., 2019).

Like skilled herders and their flocks, we humans can link our palates with foodscapes to engender human and environmental health. When the projected population increase to 10 billion people is combined with an increase of 32% in per person emissions from global shifts to ultra-processed diets high in refined carbohydrates, the net effect is an 80% increase by 2050 in greenhouse gas emissions (GHGE) from food production and consumption (Tilman and Clark, 2014). Studies in Japan and Australia support the contention that ultra-processed foods are major contributors to GHGE (Kanemoto et al., 2019; Ridoutt et al., 2020). Alternatively, diets of wholesome foods would not increase GHGE. Such diets could be any combination of fruits, vegetables, grains, seafood, eggs, dairy, poultry, pork, lamb, and beef.

The global shift away from eating wholesome diets to ultra-processed foods high in refined carbohydrates encouraged 2.1 billion people to over-eat and become overweight or obese (Schatzker, 2015; Ludwig, 2020). This was illustrated in a study where people offered ultra-processed foods (e.g., white bread, sugary cereals, reconstituted meats) ate an extra 500 calories a day compared with people offered wholesome foods (e.g., fresh fruits and vegetables, whole grains, unprocessed meat), even though the two diets were matched for energy, protein, sugar, fat, sodium, and fiber (Hall et al., 2019). Compared with wholesome foods, ultra-processed foods do little to induce satiation (physical and biochemical processes that bring a meal to an end) or satiety (processes that inhibit eating between meals). Thus, people overeat and gain weight.

Steadily embedding ultra-processed foods into our diets over the past 50 years has been an experiment of sorts for humans (Schatzker, 2015; Scrinis, 2020). Replicate this study over a few generations—in the womb, childhood, teen, and adult years—and we now have an epidemic of chronic diet-related diseases (Archer, 2014; Mennella, 2014; Provenza et al., 2015; Costa et al., 2018). Given modern dietary trends, it is foolish to think that introducing more ultra-processed foods (e.g., plant-based meat alternatives) into our diet will reverse the burden of diet-related diseases. Indeed, our experiences of the recent past provide a good idea of the likely outcome: a continued rise in diet-related diseases. Ironically, champions of ultra-processed plant-based meat alternatives purport to address issues of human and environmental health, created in part by industrial agriculture, with more ultra-processed foods and industrial agriculture.

In the end, the challenges of feeding eight billion people are not as simple as advocates on either side of the plants vs. meat debate suggest. Food systems are far too contingent on local socioeconomic and environmental conditions to enable one-size-fits-all policies (Halpern et al., 2019). Indeed, an omnivorous diet, rich in whole plant and animal foods, has the greatest potential to feed human populations globally (Peters et al., 2016; van Vliet et al., 2020, 2021).

PALATES LINK FOODSCAPES WITH LANDSCAPES

Palates link foodscapes with landscapes (**Figure 1**, sacral and solar plexus chakras), but neither the general public nor scientists can easily navigate that terrain. We get whiplash from the ever-changing advice given by authorities who rarely agree (Leroy et al., 2018). No wonder issues of diet rise to levels of religious fervor with salvation and damnation as common themes (Simoons, 1994). Nowadays, plant-based diets are in vogue and meat is under assault ethically (animal welfare), nutritionally (human health), and environmentally (land use practices and GHGE).

Global food systems, agricultural practices, and land uses are responsible for roughly a quarter of GHGE. Most emissions come from land use (especially deforestation), methane (mostly from cattle), and nitrous oxide (mainly from overuse of fertilizer and manure; Project Drawdown, 2020). Cattle, buffalo, goats, sheep, pigs, and poultry add 14.5% to GHGE (IPCC, 2019). Of that, 9.5% is producing feed (mainly for livestock in feedlots), processing and transporting meat, milk, and eggs. The other 5% of GHGE from livestock is methane from rumen fermentation and manure. Scientists come to different conclusions about how palates affect these GHGE figures.

To enhance human health and cool a warming climate, many groups contend that we must increase intake of vegetables, fruits, nuts, and legumes, and all but eliminate red meat from our diets (Lucas and Horton, 2019; Willett et al., 2019; Project Drawdown, 2020; WBCSD, 2020). Yet, limiting intake of red meat and processed meats for human health is not backed by rigorous scientific evidence (Zeraatkar et al., 2019; Zagmutt et al., 2020), nor do scientists agree that plant-based diets are the only way to cool a warming climate (van Vliet et al., 2020). Compared to plant-based foods, livestock require more land to produce a unit of food, so curbing the amount of meat in our diets could reduce the impacts of agriculture (Godfray et al., 2018; Project Drawdown, 2020). However, while plant-based diets can have lower GHGE than meat-based diets (Poore and Nemecek, 2018), when their impacts are calculated to consider nutrients, the footprints of animal and plant foods are similar because animal tissues better meet our needs for many nutrients, including all of the essential amino acids (Drewnowski et al., 2015; Tessari et al., 2016; van Vliet et al., 2021). Forsaking an omnivorous diet in favor of a plant-based diet would also mean growing more commodity crops, which due to high levels of soil erosion, could add more than livestock to GHGE (Teague et al., 2016), especially considering projected increases in soil erosion from farming (O'Neal et al., 2005).

With regard to grazing, some contend that animals on pastures have more adverse impacts than animals in feedlots, when considering both land use and GHGE. Grazing practices increase land use and GHGE when they require deforestation, synthetic fertilizers, and water to produce feed for livestock on pastures (Project Drawdown, 2020). Moreover, animals on pasture typically grow more slowly than animals in feedlots and so they take longer (18–24 months) to reach slaughter weight than animals in feedlots (12–16 months) (Swain et al., 2018). The increased time to slaughter adds to GHGE as well as the cost of meat for consumers.

Life-cycle analyses (LCA) reveal smaller carbon footprints for plant-based meat alternatives (Beyond Burger^{R} and Impossible^{TM} Burger) compared with cattle finished in feedlots (+3.2 and +3.5 kg CO_2-eq emissions/per kg product, respectively; Heller and Keoleian, 2018; Quantis International, 2019a). Values for feedlots (+10.2 to +48.5 kg CO_2-eq per kg product) depend on the geographical location where cattle are raised and GHGE potential of retail, distribution, restaurant or at home use, and end-of-life stages (Stanley et al., 2018; Asem-Hiablie et al., 2019; Rotz et al., 2019). Of note, the same company that showed a +3.5 CO_2-eq emissions/per kg product in the LCA of the Impossible Burger^{TM} (Quantis International, 2019a) also showed a −3.5 CO_2-eq emissions/per kg beef with managed grazing (Quantis International, 2019b).

How grazing is managed and the forages livestock eat influence the time to slaughter and GHGE. Due to greater soil carbon sequestration, multi-species rotational grazing can reduce net GHGE by 86%, resulting in a footprint 74% less than feedlots (Rowntree et al., 2020), and 30% less than monotonous pastures of ryegrass or alfalfa (Beck, 2020). Pasture-based livestock production that boosts diet variety improves animal welfare and production while sequestering at least as much GHG as it emits, even considering all facets of production, while enhancing ecosystem diversity and function in ways not possible with monoculture crops or pastures (Allard et al., 2007; Teague et al., 2016; Stanley et al., 2018; Viglizzo et al., 2019; Beck and Gregorini, 2020; Rowntree et al., 2020). Compared with grazing a monoculture of grass or alfalfa, when cattle or sheep eat diverse mixes of grasses, forbs, and tannin-containing legumes, they gain weight more efficiently and reach finish body condition nearly as quickly as animals in feedlots and with less GHGE (Hristov et al., 2013; Villalba et al., 2019; Beck, 2020; Thompson and Rowntree, 2020).

Alas, while livestock can be raised with fewer GHGE, and in some cases in ways that sequester more GHG than they emit, that is not so for the vast majority of the world's animal agriculture (Project Drawdown, 2020). While some studies show high sequestration rates for managed grazing, that is not consistent across all grazing operations due to factors that include soil texture, the mix of plant species, grazing intensity, and rainfall (Conant et al., 2017; Stanley et al., 2018; Paustian et al., 2019). Rainfall (water) is essential for photosynthesis, and water availability is expected to become more uncertain with climate change. Lack of water, nitrogen, and other nutrients such as phosphorus may thus constrain the size of agricultural carbon sinks (Lal, 2016).

Carbon dioxide (CO_2) absorbed through photosynthesis can be stored in grasses, forbs, shrubs, and trees, and as organic matter in soil. Depending on the form, this carbon can be stored for a season, several years, multiple decades, or several centuries. Eventually, though, carbon returns to the atmosphere *via* decomposition processes and management practices alter that outcome. Regenerative agriculture stresses improved annual cropping systems, crop-livestock integration, and managed grazing, while the benefits of silvopasture that integrate trees into working landscapes are often ignored. Yet, tree intercropping is more common than regenerative annual cropping, and silvopasture is practiced more widely than managed grazing (Project Drawdown, 2020). These practices have much higher sequestration rates than regenerative annual cropping or managed grazing, with much greater scientific certainty about their benefits (Lal et al., 2018; Project Drawdown, 2020). Where suitable, the opportunity is thus to convert pastures to silvopasture, increasing sequestration rates as well as the sale of livestock and wood products.

Predicting levels of CO_2 is difficult (IPCC, 2019). Even if we knew what would happen to man-made emissions—which depend on international policies, technological and agricultural advances—Earth's network of sources and sinks is vast, interlinked, and dynamic. To further complicate matters, climate change is projected to transform many landscapes from carbon sinks to sources due to increasing droughts, fires, and other disturbances that release carbon from soils and plants. Past IPCC estimates range from as high as 2,000 ppm by 2250 (temperature rise of 9°C) to 700 ppm by 2080 (rise of >3°C). The most optimistic scenario is one where emissions peak now and begin to decline, as we remove more carbon from the air than we produce by 2070, and CO_2 dips below 400 ppm between 2100 and 2200 (increase <1°C).

Methane (CH_4) is a greenhouse gas with 28 times the global warming potential of carbon dioxide. Methane emissions have fluctuated during the past 12,000 years (Smith et al., 2016). They were reduced by the mass extinction of wild mammals at the end of the Pleistocene Epoch 12,000 years ago. They also declined with the extirpation of bison in North America (1860's) and the rinderpest epizootic that wiped out animal populations in Africa (1890's). Methane produced by ruminants today is equivalent to that of wild mammals prior to the Pleistocene extinctions.

Nearly one third of the CH_4 emitted by human activities is from producing and transporting coal, natural gas, and oil (31%). In addition, other human activities—landfills with organic material that rots (16%), livestock (5%), and rice paddies (3%)—have also helped methane-belching microbes proliferate. Methane is produced by methanogenic bacteria in wetlands and oceans as well as in stomachs of termites and ruminants such as cattle, sheep, and goats. Enteric CH_4 emissions from ruminants can be reduced by restoring degraded farmlands, pastures, and rangelands, by managing grazing, and by increasing the nutritive quality and digestibility of forages, including planting tannin-containing forbs, shrubs, and trees in landscapes (Thornton and Herrero, 2010; Wang et al., 2014, 2015; Herrero et al., 2016; Singh and Gupta, 2016; Villalba et al., 2019).

While CH_4 is a potent GHG, it is also a temporary one. It lasts a decade before it breaks down. On the other hand, once we put CO_2 in the atmosphere, it persists for centuries. Carbon dioxide levels, now at 415 ppm, are greater than humans have ever experienced. The last time Earth's atmosphere sustained that amount of CO_2–during the Pliocene Epoch 5.3 to 2.6 million years ago—Antarctica was a plant-covered oasis, sea levels were an estimated 10 to 20 m higher and global temperatures were an average of 2–3°C warmer.

Nitrous oxide (N_2O) emissions occur *via* the circulation of nitrogen among microorganisms that live in the soil and water, plants and animals, and the atmosphere. Application of nitrogen fertilizer to soil accounts for most agricultural emissions of N_2O, which can be reduced by managing soil in ways that decrease the need for nitrogen fertilizer, applying fertilizers more efficiently, modifying manure management practices, and integrating livestock back into farming systems (Project Drawdown, 2020). Manure left on pastures is a large source of N_2O emissions. Providing livestock with tannin-containing forages decreases nitrogen in urine and increases nitrogen in manure, which reduces N_2O emissions and builds soil organic matter (Clemensen et al., 2020). The presence of plants, instead of bare soil, reduces N_2O emissions (de Klein et al., 2020). Well-managed pastures also emit less N_2O than degraded pastures (Chirinda et al., 2019), an effect that if it occurs widely, is an under-appreciated impact of managed grazing.

Grasslands absorb and release CO_2, emit CH_4 from livestock, and emit N_2O from soils. Carbon sinks are located mainly in natural and sparsely grazed grasslands, whereas emissions of CO_2, CH_4, and N_2O predominate in managed grasslands (Chang et al., 2021). From 1750 to 2012, substantial increases in livestock numbers enhanced warming due to emissions of CH_4 and N_2O that were partially offset by reduced numbers of wild herbivores. Concurrently, conversion of forests to pastures and grasslands to croplands caused net warming. Notably, the cooling effect of carbon sinks in natural and sparsely grazed grasslands has nearly canceled warming from managed grasslands. Managed grazing, pasture improvement, and restoration of degraded pastures can all help to prevent further warming from managed grasslands.

During the past century, agriculture declared fossil-fuel-based warfare on land mechanically (plowing soil), chemically (herbicides and pesticides), and biologically (GMO technology). By separating rearing livestock from growing crops, we decoupled bio- and geo-chemical cycling of carbon, water, nitrogen, phosphorus, and sulfur, and increased emissions of methane and nitrous oxide, as well as eutrophication and contamination of water sources (Lal, 2020). Agriculture can reverse ecological damage—from excess irrigation, tillage, fertilizers, herbicides, and pesticides used to grow and protect crops in monocultures—by integrating multiple species of livestock back into landscapes with different crops to build organic matter, fertility, and water-holding capacity of soil (Berry, 1977; Gosnell et al., 2020; Rowntree et al., 2020).

Of 80 ways to mitigate climate change assessed in Project Drawdown (Hawken, 2017), food and agriculture rank high: reducing food waste (ranked 2), eating plant-rich diets (4), sustaining tropical forests (5), silvopasture that combines forestry and grazing (9), regenerative agriculture (11), sustaining temperate forests (12), conservation agriculture (16), tree intercropping that combines growing trees with annual crops (17), and managed grazing (19). To reduce GHGE and sequester GHG, farmers and ranchers can combine practices—e.g., cover crops, compost applications, perennial crops, silvopasture, managed multi-species grazing—to produce food in ways that generate soil health, enhance plant and animal diversity, and provide ecosystem services including carbon sequestration (Lal, 2016, 2020; Gregorini et al., 2017; IPCC, 2019; Project Drawdown, 2020). In the process, we can grow phytochemically rich vegetables, fruits, and crops to feed ourselves and the animals in our care. We can also reduce livestock in feedlots, eat less meat in industrial nations, and increase animals grazing diverse mixtures of phytochemically rich forages to provide meat that is phytochemically and biochemically richer and arguably more nourishing for people and environments (Provenza et al., 2019; van Vliet et al., 2021).

While some individuals and organizations claim regenerative agriculture alone can halt climate change, that is not the case, and questions remain about how much emissions can be sequestered (Project Drawdown, 2020). Enthusiasm and hubris often blind us to the limits of our ability to foresee the unintended consequences of our actions. People who initiated the Green Revolution, out of the best of intentions, did not anticipate adverse outcomes, any more than John D. Rockefeller foresaw the fallout from the fossil fuels that now sustain industrial agriculture. Life is an endless series of unintended outcomes that emerge surprisingly from our best intentions. Conceding our limits with humble hearts can help keep our eyes open (Senge, 1994; Provenza, 2018). Though the Green Revolution fed billions of people, unintended costs include: (1) social changes from loss of land, massive displacement, and poverty for countless small farmers; (2) loss of biodiversity and food quality; (3) land degradation from soil erosion and loss of minerals, (4) adverse effects of synthetic fertilizers on soil organisms, (5) pollution from fertilizers, herbicides, and pesticides; (6) salinity from irrigation; and (7) fossil-fuel dependence.

The current focus on the role of agriculture in greenhouse gas emissions and sequestration neglects this fundamental issue: the ecological, economic, and social costs of our utter dependence on fossil fuels are unsustainable (Hagens, 2020). Ironically, contemporary economic models—built upon land, labor, and capital—do not reflect the singular importance to society of inexpensive energy derived from fossil fuels. To produce a calorie of food, modern industrial agriculture requires a minimum of two calories of fossil fuels for machinery to plant, irrigate, and harvest crops; for fertilizers, herbicides, and insecticides to grow and protect plants in monocultures; for antibiotics and anthelmintics to maintain the health of livestock; and for nutrition supplements and pharmaceuticals to sustain the health of livestock and humans. We use another 8–12 calories of fossil fuels to process, package, deliver, store, and cook modern food. No wild species can survive expending far more energy than it consumes.

Our reliance on fossil fuels to produce food will of necessity decline during the first half of the twenty-first century due to increasing economic and environmental costs of extracting fossil fuels and their adverse effects on people, environments, and climate. This seeming catastrophe will create opportunities for societies to produce foods locally in ways that nurture relationships among soil, water, plants, herbivores, farmers/ranchers, and consumers. Agriculture will be at the heart of communities, but from soils and plants to livestock and humans, we will need to learn what it means to *co-evolve* with nature's complex creative communities, endlessly transforming due to ever-changing relationships among organisms and environments. As part of that co-evolutionary process, plants will become important as nutrition centers and pharmacies—their phytochemicals essential in the health of plants, livestock, and people—and we will need to co-create plant and animal communities that can thrive in the absence of fossil fuel inputs (Provenza, 2008). According to Darwinian theory, plant and animal species *adapt* as genes with survival value are passed from one generation to the next. That view fosters rather rigid notions of evolution that disregard how plants and animals *create relationships* with what they deem to be relevant facets of the biophysical environments they inhabit (Lewontin, 2000; Provenza, 2018). Organisms are not machines and genes are not destiny. Rather, individuals are *involved* in the world, which allows them to *evolve* with the world (Provenza et al., 2013; Laland and Chiu, 2021). This view recognizes that the success of co-evolution depends not only on "the right combination of genes" in plants and animals but on how those genes are expressed epigenetically in the environments where people and the plants and animals in their care are co-evolving. Co-evolution also involves learned behaviors, passed from one animal generation to the next, in which mother and extended families are transgenerational linkages to landscapes.

HEARTSCAPES LINK PALATES WITH FOODSCAPES AND LANDSCAPES

The heart chakra, which is the conduit from the root, sacral, and soler plexus to throat, third eye, and crown chakras, reflects our ability to give and receive love, the basis for our capacity to nurture plants, animals, and people. Creating ecologically sustainable foodscapes is a challenge for the industrial ways we produce, market, and consume food, which do little to promote and nourish diverse communities of life below and above ground. That includes both conventional and regenerative agricultural practices when they do not address the social inequities and structural racism at the heart of agriculture by enhancing the diversity of people who produce food locally in ways that enhance food security (Gregorini and Maxwell, 2020; Wozniacka, 2021). Such systems do not encourage socio-economically inclusive relationships that link heartscapes with foodscapes and landscapes. All of these interrelated factors influence what people want to eat. For example, when we think about how the different foods that we eat may affect changing climates, biodiversity, human and animal well-being, and then feel compassion for the collective consequences, some people lose their appetite for eating animals.

Based on data from the United Nations FAO (2020), more than 72 billion cows, sheep, goats, pigs, and chickens are killed annually to help feed 7.8 billion humans worldwide. While people in government and industry focus on how much meat is produced and consumed, farming is also about the lives of plants and animals—and the quality of their lives. While the inner life of a farmed animal depends on the species—each has its own nature and each one his or her own life—the scientific literature on everyone from chickens to cows leads to one conclusion: farmed animals are beings who possess many of the emotional and mental traits of humans (Marino, 2019). Because most people lack intimate relationships with raising the plants and animals they consume, we lack awareness of their sentience—their capacity to feel, perceive, and experience life subjectively. And though the poor quality of life and violent death suffered by factory-farmed animals is well-documented, many people ignore this evidence in favor of beliefs that meat is merely a commodity we purchase from the grocer (Leroy and Praet, 2017).

In the U.S., only 4% of calves spend their entire lives on pastures and rangelands eating phytochemically rich plants. The other 96% of calves are weaned at 7–8 months of age and moved to feedlots or monotonous pastures to be fattened. In many cases, these conditions violate the five freedoms of animal welfare: freedom from fear, distress, discomfort, pain, injury, and disease (Manteca et al., 2008; Mellor, 2016; Villalba and Manteca, 2019). Calves are moved from familiar (mother, peers, home pastures) to unfamiliar (feedlots) haunts, which causes fear and distress. Though individuals differ in preferences due to experiences *in utero* and early in life (Atwood et al., 2001; Wiedmeier et al., 2012; Beck, 2020), they have no chance to self-select their own diets, which violates their freedom to express normal behavior, maintain health, and avert disease. Like us, they dislike any food eaten too often or in excess, which causes stress and food aversions (Catanese et al., 2013). Yet, daily they are fed the same feedlot ration, or pastures of ryegrass or alfalfa, so monotonous and high in grain or nitrogen they experience nausea, causing discomfort and distress (Provenza et al., 1994; Beck and Gregorini, 2020).

Collectively, these practices cause animals in feedlots to suffer various maladies, including liver abscesses, chronic acidosis, oxidative and physiological stress, and other metabolic diseases similar to people with metabolic syndrome, characterized by muscle mitochondrial dysfunction, oxidative stress, and elevated levels of blood glucose, insulin, and cortisol (Carrillo et al., 2016; Beck and Gregorini, 2020; van Vliet et al., 2021). In contrast, the greater mitochondrial oxidative enzyme levels in animals eating phytochemically rich diets are analogous to those in healthy athletes (Apaoblaza et al., 2020). To counter the effects of phytochemically poor diets on morbidity and mortality (Maday, 2016), animals are sustained on antibiotics, whose overuse in feedlots helped create antibiotic resistance. Increasing intake of meat from livestock reared on phytochemically rich foodscapes, while reducing intake of meat from feedlots, could improve animal welfare, reduce excessive intake of meat, and increase intake of phytochemically and biochemically rich meat of better quality (Provenza et al., 2019; van Vliet et al., 2021).

Because most people do not raise the animals and plants they eat, many believe farm animals and cultivated plants lack intelligence, awareness, or concern about the quality of their lives. That view goes back to Aristotle, who assumed animals differ from people because people can reason. He credited animals, but not plants, with perception—awareness gained through senses. Fast-forward 2,400 years and plant physiologists and molecular biologists are presenting compelling evidence that plants possess states of perception and awareness—gained through as many as 20 senses—far beyond what the ancient Greeks knew (Chamovitz, 2012; Trewavas, 2014). If we consider consciousness and sentience to be part of awareness and perception, then some contend that plants are conscious and sentient (Mancuso, 2018). Moreover, learning and memory are vital as roots, stems, leaves, and flowers address environmental challenges.

Vines and roots know when they "touch" their own shoots and roots or those of other plants. Roots interact with fungi and bacteria, collectively known as the plant microbiome, as they "forage" for water and nutrients: roots transfer energy from leaves to fungi and bacteria and they transfer nutrients from fungi and bacteria back to the host plant. Root exudates contain primary and secondary metabolites that can attract, deter, or kill belowground insect herbivores, nematodes, and microbes, and inhibit competing plants (van Dam and Bouwmeester, 2016).

Plants "see" different wavelengths of light, which they capture in photosynthesis. As part of that process, they "breathe" through stomata on the surface of leaves and stems. They open their stomates to inhale carbon dioxide—which they use to fashion rich arrays of phytochemicals—and they exhale oxygen, processes that are metabolic counterparts in animals and humans.

Plants can "smell" and "taste" compounds in the air and on their tissues; they can "hear" and respond to the sound of a caterpillar chomping on a neighboring plant; they "smell" and "taste" and "talk" and "listen" in a biochemical language using phytochemicals (Karban, 2015). Volatile compounds produced by one plant can alert its neighbors to danger; harken insect predators to protect them from would-be insect foragers; recruit animals to perform vital services such as pollination and seed dispersal; and deter herbivores from eating too much of their tissues.

What should we think, then, about the multidimensional interrelationships that plants create with soil organisms, other plants, and animals? What kind of intelligence is being manifest? When organic chemists synthesize compounds in labs, we consider that an act of high intelligence, as any student who has taken a class an organic chemistry will attest. Yet, plants routinely outmaneuver clever chemists, agri-business, and farm folks who attempt to eradicate them with chemicals, as over 500 herbicide-resistant weeds worldwide can attest (Heap, 2020).

Nobody knows how a plant or an animal or another person experiences life, but the fact that we share many attributes presents humans with a conundrum that lies at the heart of a mystery: for any being to live, other beings must die. While eating a plant-based diet or plant-based meat does not directly involve killing animals, indirectly it does. Crops are grown in monocultures where life below and aboveground is destroyed by tillage, pesticides, and fertilizers (Fischer and Lamey, 2018). Along with numerous other species (Kolbert, 2014), a striking example is grassland birds whose numbers declined by over 50% in the last 50 years due to industrial agriculture (Rosenberg et al., 2019). Conversely, regenerative practices that integrate livestock with farming can nurture life below and above ground in ways not possible with fossil-fuel intensive industrial agriculture (Horrigan et al., 2002). Though not a panacea for saving the planet, such practices could be a vital step in the right direction (Smith, 2014; Massy, 2017; Brown, 2018; Godde et al., 2020), but that will require transforming fossil-fuel dependent industrial agriculture into ecological agriculture.

While most people do not own farms or ranches, anyone who owns a plot of land can become a farmer and a rancher, nurturing biodiversity by creating homes for plant and animal species on their land. We can grow lawns "infested" with clover and dandelions, so we don't have to fertilize with nitrogen or use herbicides. Better yet, we can encourage native plant species that thrive in our landscapes to diversify life below and aboveground in our neighborhoods. We can grow vegetable, herbal, and medicinal gardens and raise bees and chickens. We can plant native shrubs and trees that sequester carbon and provide flowers and berries for bees and birds. In so doing, we reduce our need for water, the lifeblood of this planet, and fossil fuels to grow, fertilize, weed, and mow lawns. Just as meaningfully, growing plants and animals that become food for our bodies will help us appreciate that all life—plant and animal alike—is sacred, a gift from Nature's bounty that can be shared with our community, who in turn return the favor.

Nearly 75 years ago in *A Sand County Almanac*, Aldo Leopold warned of the dangers of breaking our linkages with the plants and animals and ecosystems that nurture and sustain us: "There are two spiritual dangers in not owning a farm. One is the danger of supposing that breakfast comes from the grocery, and the other that heat comes from the furnace. To avoid the first danger, one should plant a garden, preferably where there is no grocer to confuse the issue. To avoid the second, he should lay a split of good oak on the andirons, preferable where there is no furnace, and let it warm his shins while a February blizzard tosses the trees outside."

Becoming involved in the natural world would change our relationships—socially, ecologically, and economically—with the communities we inhabit. Economics is decision-making in the face of scarcity based on commodification of goods and services. Scarcity is requisite for capitalist economies to function and they are designed to create scarcity where it does not exist (Hagens, 2020; Kimmerer, 2020). To our collective detriment, monetized systems do not link people with one another and mother Earth out of gratitude and reciprocity for one another and nature's bounty as members of her community. These currencies of a gift economy multiply with each exchange as their life-giving energies ripple outward from person to person.

"Gratitude is the thread that connects us in a deep relationship," notes Robin Wall Kimmerer, "simultaneously physical and spiritual, as our bodies are fed and spirits nourished by the sense of belonging, which is the most vital of foods. Gratitude creates a sense of abundance, the knowing that you have what you need. In that climate of sufficiency, our hunger for more abates and we take only what we need, in respect for the generosity of the giver." If our first response is gratitude in a gift economy, then our next response is reciprocity to the giver and our mother.

Kimmerer concludes: "Continued fealty to economies based on competition for manufactured scarcity, rather than cooperation around natural abundance, is now causing us to face the danger of producing real scarcity, evident in growing shortages of food and clean water, breathable air, and fertile soil. Climate change is a product of this extractive economy and is forcing us to confront the inevitable outcome of our consumptive lifestyle, genuine scarcity for which the market has no remedy... Regenerative economies which cherish and reciprocate the gift are the only path forward. To replenish the possibility of mutual flourishing..., we need an economy that shares the gifts of the Earth, following the lead of our oldest teachers, the plants."

Modern *Homo sapiens* have made an art form of dining, but we tabled the larger questions concerning our relationships with the heartscapes we inhabit socially, ecologically, and economically. Eating is participating in endless transformation. As I eat, energy and matter in someone—plants and animals alike—becomes this entity I call me, which will, in the flicker of a cosmic eye, become soil, plants, and animals again. In pondering this mystery, we may realize that all life is sacred (**Figure 1**, heart chakra). The well-being of the plants and animals we eat to nourish our bodies determines our health and that of the communities that sustain life on Earth.

FROM FOODSCAPES, LANDSCAPES, AND HEARTSCAPES TO TRANSFORMATIONS OF THOUGHTSCAPES

Thoughtscapes refers to the topography of mind-body consciousness, the awareness of the thinker and knower of our spatial and temporal interdependence and at-one-ness with foodscapes, landscapes, heartscapes, and communities (Gregorini and Maxwell, 2020; **Figure 1**, third eye and crown chakras). If we identify solely with "my" self, we create an impermeable wall of perceptions, beliefs, and judgments that block our relationships with one another and the communities we inhabit. As Tolle (1999) puts it: "It is the screen of thought that creates the illusion of separateness, the illusion that there is you and a totally separate "other." You then forget the essential fact that, underneath the level of physical appearances and separate forms, you are one with all that is. By "forget," I mean that you can no longer *feel* this oneness as self-evident reality. You may *believe* it to be true, but you no longer *know* it to be true."

When foodscapes, landscapes, heartscapes, and thoughtscapes are allied, we *feel* connected and aligned with one another and nature's communities. "The word enlightenment conjures up the idea of some super-human accomplishment," as Tolle notes, "and the ego likes to keep it that way, but it is simply your natural state of *felt* oneness with Being. It is a state of connectedness with something immeasurable and indestructible, something that, almost paradoxically, is essentially you and yet it is much greater than you. It is finding your true nature beyond name and form. The inability to feel this connectedness gives rise to the illusion of separation from yourself and the world around you. You then perceive yourself, consciously and unconsciously, as an isolated fragment. Fear arises, and conflict within and without becomes the norm."

Historically, the quest by many human populations to dominate nature was a core civilizing force and a natural impulse when humanity was exposed and vulnerable to the elements (**Figure 1**, root, sacral, and solar plexus chakras). Nature, as we know, is often unkind. Through our desire to protect ourselves from the harshness of Earth's vagaries and to feed, clothe, and house ourselves, we came together in extended families, formed tribes, cities, states, nations, and civilizations. This impetus was further enabled and driven by a hierarchical structure that placed our God or the Gods, depending on one's mythology, at the top with humans within "our group" next, followed by "other" humans not within "our tribe," then came animals (valued for how they supported human efforts to overcome nature) and plants (as a way to feed livestock and humans).

As our technological and industrial systems developed, and we forgot our dependence on nature, we began to think ourselves more powerful than her, and if anything, came to see technology as superior to nature. Our status on top of the fossil-fuel reliant technological pyramid caused us to believe that we had "mastered nature" solely for our purposes. She is reminding us—as droughts, fires, and floods ravage the globe, warming climates cause sea levels to rise, and the coronavirus wreaks havoc on peoples and economies globally—that she is the final arbiter. These threats know no boundaries—ecologically (climate change), economically (global recession), or socially (coronavirus pandemic)—only interdependencies: our collective fates are intertwined.

Our species is now participating in the sixth mass extinction (Kolbert, 2014), facing the greatest challenges we have ever encountered: nearly eight billion people trying to deal with changing climates ecologically; disparity between haves and the have-nots economically; and xenophobic fear and hatred socially. Historically, the intersection of social, economic, and ecological issues emerged as part of the conservation movement in the land of immigrants (America) when the first national park was founded, ironically in part to "protect" land from Mexicans and Native Americans (Cagle, 2019). Eco-xenophobia resurfaced in the 1970's as overpopulation and resource depletion became issues (Ehrlich, 1968). Population growth and resource depletion were conflated with immigration growth, and both were blamed for the looming collapse of Spaceship Earth, a worldview that inspired eco-nativists and nationalists. The worsening climate crisis could easily become a bludgeon for more anti-immigration and nationalist activists.

Today, people worldwide are as polarized as they have ever been. We have forgotten the unmanifest (unity) that underlies the manifest (duality). We have forgotten that creativity comes from the union of "pairs of opposites." We are stuck in "is not" and can't recall "neither is nor is not." Ironically, some people who ascribe to world mythologies that should unite us—love your enemies—instead choose to antagonize, polarize, and isolate us from one another and our mother, as manifest through a lack of empathy and sympathy for other inhabitants on Earth. We will see if mythologies—based on loving kindness and compassion—are more than just words.

Eckhardt Tolle asks: "How is it possible that humans killed in excess of 100 million fellow humans in the twentieth century alone? Humans inflicting pain of such magnitude on one another is beyond anything you can imagine. And that's not taking into account the mental, emotional and physical violence, the torture, pain and cruelty they continue to inflict on each other as well as on other sentient beings on a daily basis. Do they act in this way because they are in touch with their natural state, the joy of life within? Of course not. Only people who are in a deeply negative state, who feel very bad indeed, would create such a reality as a reflection of how they feel. Now they are engaged in destroying nature and the planet that sustains them. Unbelievable but true. Humans are a dangerously insane and very sick species. That's not a judgement. It's a fact. It is also a fact that sanity is there underneath the madness."

The trials we now face could transform consciousness in ways that recreate our relationships with one another and life on Earth. Indeed, insufferable trials are likely the only way humanity will change. If we survive, we may be re-born in ways echoed in the Maori proverb *Ko au te whenua. Ko te whenua Koau: I am the land. The land is me.* We may come to appreciate that all political and economic prowess comes from our mother. We are the Earth, and the Earth is us. While death can transform—and near-death experiences cause some to return to Earth when they realize heaven is a state not a place (Eadie, 1994; Alexander, 2012; Moorjani, 2012)—we need not die to transform. Ordeals such as depression, cancer, divorce, and covid-19 can increase our appreciation for others and our place in the cosmos (Tolle, 1999; Bronson, 2002). Either way—dying and coming back or dying to past worldviews—trials transform.

People in rural areas worldwide are experiencing unprecedented rates of depression and suicide due to the lack of belonging that links communities socially, economically, and ecologically. Fundamental changes can occur through personal transformations of consciousness (Gosnell et al., 2019). In *Call of the Reed Warbler*, Massy (2017) discusses transformations that caused people to change agricultural practices when conventional ways no longer worked to the point that farmers were broke economically, bankrupt ecologically, and depressed socially. They first had to understand how landscapes function ecologically and how they are linked economically and socially: nothing functions in isolation. They next had to get out of the way to let these functions regenerate naturally. Finally, they had to develop the humility to "listen to the land" and embrace change while simultaneously continuing to learn with childlike openness.

Just as trials can transform our individual consciousness, global trials could transform the collective consciousness of humanity from ethnocentric and xenophobic to one that respects, nourishes, and embraces all life on Earth. Historically, our tribal nature served us well, but we are now a mutually interdependent global population inhabiting a tiny orb in the vastness of time and space. By nature, we learn early in life to identify with our family, then our community, our culture, our religion, our politics, our job, our country, and so forth—all of the "I am's." But that is an illusion inflected locally in time and space. Change the time and place, and the "I am's" change. Transcend the "I am's" and we come to the unmanifest *I am* (infinite being), which is manifest in the here-and-now as energy and matter transforming endlessly and experienced as a fleeting visit to Earth (Dunn, 1985; Tolle, 1999; **Figure 1**, third eye and crown chakras).

In a similar vein, Albert Einstein mused, "A human being is a part of the whole, called by us 'Universe,' a part limited in time and space. He experiences himself, his thoughts and feelings as something separate from the rest—a kind of optical delusion of his consciousness. The striving to free oneself from this delusion is the one issue of true religion. Not to nourish it but to try to overcome it is the way to reach the attainable measure of peace of mind." (Calaprice, 2005). Or, as Confucius taught, the task before us is to free ourselves from this prison by expanding our circle of compassion to embrace all of humanity and the whole of nature in its wonders (Smith, 1991). Transcend all of the "I am's" and we come to *I am* as an enlightened being.

Koestler (1978) coined the term "holon" to describe the interconnectedness of all things—from subatomic particles and atoms to cells and organ systems to social and biophysical landscapes to planets, solar systems, stars, and galaxies—literally worlds within worlds within worlds, each unique. He stressed that each holon has two conflicting propensities: one is integrative (to function as part of the larger whole) and the other is self-assertive (to safeguard individual autonomy). At any level of organization, each holon must affirm its individuality, but it must also yield to the demands of the larger whole for the system to function co-evolutionarily. While these two tendencies appear to be opposites, they can be harmonious and complementary. Indeed, a healthy system—cell, individual, society, and ecosystem—maintains a balanced yet dynamic interplay between integration and self-assertion that keeps a system flexible and open to change. Flexibility is lost when any holon—from cells (cancer) to individuals (political parties) to societies (nation states) to ecosystems (population explosions)—comes to dominate.

Ecologists who attempt to understand interrelationships among soil, plants, and animals are participating in an endeavor that began during the seventeenth century. Prior to that time, the predominant worldview was one of a spiritual, organic, living universe that was mysterious and, in some ways, frighteningly unpredictable. That view changed in the seventeenth century to one in which nature, though complex, was thought to be knowable and predictable, provided we could just discover the rules. The machine became the model and the clock the metaphor for this worldview, but the more we learn about the workings of the clock, the more intricate, complex, and mysterious the "machine" becomes. We can understand the rules of nature's game, but the flexibility of the processes enables life to evolve with ever-changing conditions (Provenza, 2018). Rather than machine-like, fixed, and rigid, genes are expressed epigenetically, which enables plants and animals to change morphologically (form), physiologically (function), and behaviorally as social and biophysical environments change.

The ability to perceive the world differently is far more important than any scientific knowledge we appear to gain about the workings of soils, plants, animals, people, and the environments we inhabit. Each time we look more deeply at any "essential thing" it turns out to have some other feature of appearances, such that in the manifest we will never reach a "final essence" which is not also the appearance of something more. Manifold manifestations arise from the transcendent (**Figure 1**, Crown Chakra). As visionary physicist David Bohm put it (Horgan, 2018): "Anything known has to be determined by its limits. And that's not just quantitative but qualitative. The theory is this and not that. Now it's consistent to propose that there is the unlimited. You have to notice that if you say there is the unlimited, it cannot be different, because then the unlimited will limit the limited, by saying that the limited is not the unlimited, right? The unlimited must include the limited. We have to say, from the unlimited the limited arises, in a creative process."

We are thus coming to view science, not as a predictive oracle, but rather as a way to understand creative processes of nature and to monitor and assess policies implemented through consensus. Playing nature's game is about flexibility in the face of ever-changing environments. Flexibility is about taking small steps and keeping our eyes open. Consensus helps us choose where to walk. Science helps our eyes to open and focus. In that sense, the challenge is to understand principles, processes, and interrelationships. The opportunity is to meld science with the local knowledge of people making their livings on landscapes that are uniquely regenerating in time and space.

What will become of *Homo sapiens*? No one knows the answer to that question: an individual, a species, a universe—all are ever changing verses in the language of *I am*. But at this moment on this planet the question is not if life on Earth will continue. The question is if *Homo sapiens* can learn to live with respect for one another and the other inhabitants of this planet.

Human civilizations typically last 10 generations, roughly 250 years, as they evolve through five stages: pioneers, commerce, affluence, intellect, and decadence (Ophuls, 2012). Civilizations collapse due to combinations of factors that include exceeding biophysical limits, excessive complexity, and human errors that involve practical failures and moral decay. Historically, the consequences of a failed civilization were catastrophic for a particular society, but they were not fatal to *Homo sapiens* as a species. We now live in an interdependent, global civilization, in which the destinies of all peoples are intertwined socially economically, and ecologically.

The Maori term *Taiao* speaks to our linkages with the natural environment that surrounds us, encompassing the world and her offspring. Because we are born of the Earth, we have an eternal connection to *Taiao*, which is about forging nourishing relationships with one another and our mother as we find our way forward (Morishige et al., 2018). We are members of nature's community. What we do to them, we do to ourselves. By nurturing them, we nurture ourselves.

We nurture by declaring love—not war—on one another and the communities we inhabit. Yet, human societies declare war on anything that threatens constancy, from diseases and invasive species, to one another. As Campbell (1972) noted: "It is for an obvious reason far easier to name examples of mythologies of war than mythologies of peace; for not only has conflict between groups been normal to human experience, but there is also the cruel fact to be recognized that killing is the precondition of all living whatsoever: life lives on life, eats life, and would otherwise not exist. To some this terrible necessity is fundamentally unacceptable, and such people have, at times, brought forth mythologies of a way to perpetual peace. However, those have not been the people generally who have survived in what Darwin termed the universal struggle for existence. Rather, it has been those who have been reconciled to the nature of life on this earth. Plainly and simply: it has been the nations, tribes, and peoples bred to mythologies of war that have survived to communicate their life-supporting mythic lore to descendants."

That quest created nations that now inhabit this blue orb, floating in the eternal silence of space, as astronaut Rusty Schweickart expressed so poignantly (Senge, 1994, p. 368-371): "You look down there and you can't imagine how many borders and boundaries you crossed again and again and again. And you don't even see 'em. At that wake-up scene—the Mideast—you know there are hundreds of people killing each other over some imaginary line that you can't see. From where you see it, the thing is whole, and it's so beautiful. And you wish you could take one from each side in hand and say, 'Look at it from this perspective. Look at that. What's important?'... The size of it, the significance of it—it becomes both things, it becomes so small and so fragile, and such a precious little spot in the universe… and you realize that on that small spot, that little blue and white thing is everything that means anything to you. All of history and music, and poetry and art and war and death and birth and love, tears, joy, games, all of it is on that little spot out there…" (https://www.youtube.com/watch?reload=9&v=zmHrnKY6crE).

On the one hand, we miss the point if we believe that Eden comes after we die. Eden is right here, right now. Heaven and hell and all the gods are in us, not somewhere out in the cosmos (Campbell and Moyers, 1988; Moorjani, 2012). If we value this dimension of Eden, we must nurture this Garden, treat this dwelling and its inhabitants with love and respect. But if our love of money, power, and dominion continue to trump the power of love for one another and our mother (Reich, 2015; Mayer, 2017; Kimmerer, 2020), we will be expelled from the Garden. We will continue to plunder one another and our mother as long as our contrived views of socio-economic and ecological systems are based on scarcity, selfishness, greed, and competition, rather than abundance, selflessness, sharing, and cooperation. If we appreciate that we are the children of Earth, we may learn to thrive with one another and all life in the Garden.

On the other hand, as Smith (1991) reminds us with regard to Hindu beliefs: "All talk of social progress, of cleaning up the world, of creating the kingdom of heaven on Earth—in short all dreams of utopia—are not just doomed to disappointment; they misjudge the world's purpose, which is not to rival paradise but to provide a training ground for the human spirit." Likewise, as Campbell and Moyers (1988) put it succinctly: "When we talk about settling the world's problems, we're barking up the wrong tree. The world is perfect. It's a mess. It has always been a mess. We are not going to change it. Our job is to straighten out our own lives."

So, we must each make a choice: an eye for an eye, a tooth for a tooth or love your enemies. Do we want blind, toothless inhabitants of Earth or do we want to nurture one another and life on Earth? Do we want lives motivated merely by the needs and wants of the root, sacral, and solar plexus or do we seek as well a transformation at the heart chakra to loving kindness, awareness, and enlightenment? These issues have little to do with ecological and economic matters *per se*. Rather, the issue is transcending the "I am's" to heal divides that polarize and isolate us. The irony is if we work together to transcend the boundaries we create, we will address "the really big issues" by nurturing the creativity and diversity needed to overcome the challenges we now face. And though we could continue to declare war on life, as we have done, we could instead declare love on one another through the foodscapes, landscapes, heartscapes, and thoughtscapes we choose to inhabit. Time will tell which alternative we choose and how the choices we make will emerge as we participate in co-creating with (or without) one another and our mother.

AUTHOR CONTRIBUTIONS

FP wrote the manuscript. CA and PG contributed valuable input throughout the process. All authors contributed to the article and approved the submitted version.

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Pastoral Agriculture in the Post-industrial Age: Building Functional Integrity and Realising Potential

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The potential of pastoral land use to create positive environmental, economic, and social outcomes is constrained by a "way of seeing" land and people through the eyes of Modernity and mechanical determinism. That ontology of land is compounded and reinforced by positivism, and the associated hierarchical and dis-integrated epistemology around the culture:nature nexus – including what is seen as "objective" science and technology driving practise. Both the ontology and epistemology of our Modern land use culture drive a reduction of ethics, relationship, and meaning to the measured utility of either production or dollars within a "resource sufficiency" view of the land factory. The consequence is not just the non-realisation of potential synergies and multiple functions underpinning value and resilience within the socio-ecological systems associated with pastoral land. It also degrades the "functional integrity" of those integrated systems and increases the fragility and multiple negative outcomes to local economic, environmental, and social functions. This study examines the underlying philosophical thoughtscapes of Modern agri-business models and contrasts those models with the emerging alternatives: from reducible universally-quantifiable machines to post-industrial thought; including post-normal science, integrated complex adaptive systems, and emerging work shifting homogeneous "economies of scale" industrialism to realising potential "economies of scope" by building functional and self-organising systems. It further examines the potential scope to be gained using three specific examples: multi-functional integrated landscapes, resilience theory specific to drought, and market value chains.

Keywords: functional integrity, socio-ecological systems, agroecological systems, ontology of land, economies of scope, post-industrialism, agricultural industrialism

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CONCEPTUAL ANALYSIS: INTRODUCTION

> *"There are these two young fish swimming along, and they happen to meet an older fish swimming the other way who nods at them and says, "Morning, boys. How's the water?" And the two young fish swim on for a bit, and then, eventually, one of them looks over at the other and goes, "What the hell is water?"*

David Foster Wallace "*This Is Water: Some Thoughts, Delivered on a Significant Occasion, about Living a Compassionate Life*"

Landscapes are a contest of ideas. We "see" them through a cultural lens – from sinister to transcendent, as agronomic resources or pure cultureless nature, as utility or memory, and as "other" and outside ourselves; we also see them as integrated with their community and as interconnected systems, complex, uncertain, constantly in flux, constantly in contact with multiple domains. Such cultural "lenses" – whether called paradigms, worldviews, framings, or metaphors by which we see and live – are built within us through upbringing, education, and through our own reflexive relationship with any particular piece of land (Glenna, 1996).

We are also influenced by the dominant power relationships and wider political ecologies within which research, policy, and practise reside. That is the wider context. However, the focus of this paper is on the ideas underpinning research, policy, and practise rather than a comprehensive examination of the wider political ecologies at both national and international levels, including those particular and growing shifts in power relationships as local 'grass roots' communities challenge the dominant framing and practises associated with land and community.

Landscapes are thoughtscapes, not objective spaces. We see what the constraints and scope of our cultural lens allows us to see. What we create reflects what Pierre Bourdieu defined as *Habitus* (Bourdieu, 1977): the customary, "pre-law" practises we see as right and wrong and good and bad, all associated with a personal culture within, which both limits and allows. Within one culture, someone will eat a dog without a thought. In another, they will not. "This is what we do."

What we make of a landscape, a farm, or its associated community, is a manifestation of *Habitus*. The landscape we make reflects back on us, usually in confirmation. It is not just the practise of people more intimate with land who see and create this way, it is the institutions of government (Scott, 1999), policy making, commerce, education, and research.

For those of us raised in the non-Humanities disciplines, in supposed "facts," such deeper questions are uncommon. We deal in the implicit analytical and "positive" traditions: in uncontested assumptions of objective measured things. We tend to measure what can fit within our methods, our assumptions of metaphysics and epistemology, and even by what is easily measured in time and place. The path of least resistance is studied. The less easy road, however more important, waits its turn.

This underlying sociology of research and practise is not the premise of any call to dismiss all actions as relative. It is a call to consider what lies beneath; particularly to first acknowledge and then question the Modern and positivist mechanical metaphysical ideas that currently underpin the questionable industrialism of land and community. From that acknowledgement, the questions of appropriateness and alternative naturally flow.

There are alternatives. Arguably one of the big three scientific shocks of the twentieth Century, alongside Einstein's Relativity and Heisenberg's Uncertainty Principle, was Complexity Theory (Gleich, 1987). The reductionist Newtonian world of universal rules does not relate well to all contexts.

People are obviously one of those contexts, where a Newtonian approach reduces humanity to a set of biophysical measures, destroying the essence of humanity, reducing potential and increasing the chance of dysfunction and failure. Extreme examples illustrate the point. Newtonian Behaviourist experiments in raising animals and children as machines – the post-Soviet Romanian orphanages: the live vivisection of what were presumed to be the animal "machine" of the seventeenth and eighteenth centuries – are examples of wrongly framing a Complex Adaptive System as simple machines; none of these can be objectified and reduced without the serious loss of something, including morality.

For land and their communities – socio-ecological systems – the same questions require an answer. Can land and communities be reduced in such a way, without a significant loss of perspective, that is sufficient to lose not just a sense of right and wrong but also an awareness of the consequences of what we do?

A landscape and the ecosystems within are inherently multifunctional, interdependent, complex, and adaptive. Include culture within that nature, not just as framed by socio-ecological research, but also through the functions of economics, and that land is more complex still.

Newtonian regularity in such a context is an ontological fallacy; it is no more logical than reducing a child to a calorie input-output machine.

We lose potential and increase "unforeseen" problems when we look to our landscapes through the industrial lens of Modernity. We lose values, and opportunities by seeing the world so.

Many of those losses and gains relate to the potential "scope" of mutualisms and synergistic landscape functions – ecological, economic, and social – that the analytical single-disciplinary mind is trained not to see, and therefore either not realise, or to destroy.

THE MACHINE AND THE SYSTEM

Within land use, the reducible machine metaphor makes us create factories out of a place that is very far from a machine. It is partly responsible for the declining state of our environment, especially where complex adaptive socio-ecological systems are first reduced to the metaphor of utilitarian "natural resource," and further still to the measure of those preferred "resources" like short-term agronomic production or dollar within a subjectively bounded factory space.

This reduced "field" of the study of various production variables limits the extension of thought to the wider system to landscape ecological function, sociology, climate, river, soil, energy, carbon, or wider consequences. But the statistics within the confines of the study of production can be significant if that be the mark of technocratic success. That significance can create a reflexive validation in the mind of the method, the question, and the mechanical worldview. "Science-led" is no recommendation if the question of "what science and whose science?" is not asked.

The mechanical framing can be the very basis for breaking down vital functional connections because within a synthetic connected space such as a landscape, *ceteris paribus* (all else remains constant) does not hold. In systems theory, you never do just one thing. This practise is connected to this animal and the crop, the animal to the pasture, the pasture to the soil, the soil to fertility, infiltration, root access, erosion, and water-holding capacity, those functions to hydrology, to stream systems, and so on.

The biophysical landscape is itself highly complex. Then add interactions with other interrelated systems; to the landscape's resilience to meteorological events of flood and drought, to cost and return, to market position, to diversity and business risk, to energy demand, to particular dependencies, to productivity (output/input), and to business viability. Consider effects on the well-being of an individual, the household, to the workforce, to their conditions, to local ownership structure, to local community, and to the local service town economics.

Wicked Problems and the Machine

> *"If we go through a list of some of the main* problematiques *that are defining the new Century, such as water, forced migrations, poverty, environmental crises, violence, terrorism, neo-imperialism, destruction of social fabric, we must conclude that none of them can be adequately tackled from the sphere of specific individual disciplines. They clearly represent transdisciplinary challenges. This should not represent a problem as long as the formation received by those who go through institutions of higher education, were coherent with the challenge. This is, unfortunately, not the case, since uni-disciplinary education is still widely predominant in all Universities."* (Max-Neef, 2005)

If we can never do just one thing within complexity, it follows that, if we want to understand and act wisely, we need to be as synthesising as we are analysing. This is the nature of "wicked problems" (Brown et al., 2010): multi-causal, in flux, with multiple connections. Effective analysis requires a synthesising context. Any context-less focus exacerbates the problem, not the reverse. Complex landscapes are not the place for hard-boundary discrete disciplines of knowledge treating each other as immutable billiard balls. Complexity and multiple connections (constantly shifting with context) requires a reimagine from an approach looking to *single* disciplines communicating across fixed boundaries. Not just to a *multidisciplinary* approach integrating across academia, but to a *transdisciplinary* approach inclusive of the field. Transdisciplinary research invites land users to be co-researchers within the knowledge system (Max-Neef, 2005).

COMPLEXITY, EPISTEMOLOGY AND POST-NORMAL SCIENCE: THE UNCERTAIN AND THE UNCONTROLLABLE

> *"To use the traditional scientific method to deal with issues where facts are uncertain, stakes are high, values in dispute and decisions urgent is to be like the drunkard who lost his keys. Although he had misplaced them elsewhere, he looked for them under the street light because it was the only place where he was able to see. The problem is that the key is not there, we don't even know if there is a key, and the light of the lamppost is getting weaker"* [Silvio O. Funtowicz, quoted in Tognetti (1999)].

The ability to synthesise and think into the future is arguably more necessary now than in the past. We live in interesting times, and the future is likely to get even more interesting. There is a nexus of major future issues that will impact seriously on what the future will be – peak oil, energy constraints, population pressures, other resource constraints, including water, reduction in biophysical capacities, including soils, food production and distribution, fundamentalisms of all ilk, and climate change.

Coinciding with that nexus is the emerging ground shift in the philosophy of science as well. The idea that the world can be constructed as a complicated machine is shifting to ideas related to complex systems.

> "*[A]n increasing interest in complexity [. . .] has lead to a growing recognition that real world systems can't be completely designed, controlled, understood or predicted as tradition would have it. When organisations do succeed, it's frequently been in spite of, not because of, the way they've been lead, organised and structured. The fact remains that the majority of organisations are still being managed as if they were simple, linear, equilibrium-seeking, and isolated systems, whereas complex research has decidedly demonstrated that thriving organisations are better understood as complex, nonlinear, far-from-equilibrium, and in vital contact with multiple environments."* (Goldstein et al., 2004)

The factory model of land is being replaced by models that focus on complexity, options, resilience in the face of uncertainty, and building adaptive capacity. However, the mechanical paradigm, with its Newtonian ideal of governing mathematical regularities, persists, like the alchemists and the Ptolemaic astronomers, loyal unto death to an old idea.

As with any complex system, the challenge in shifting from the Modern epistemological construct of Bacon, Descartes, and Newton changes our expectations of predictability and control. **Figure 1** is an adaptation of Peterson (Peterson et al., 2003) who challenged our scientific obsession with determinism and reductionism. Most of the world is not like that; certainly not land use systems. Research, policy and practise within the outer realm of complexity and uncontrollability requires different thinking. A similar schema was modified by Funtowicz and Ravetz (1993) and Ravetz (2006) in theorising a post-normal science that – rather than presuming an ideal of universal regularity and prediction – shifts to an ontology that accepts conditions of uncertainty and complexity (post-normal science) where decision stakes are high.

The spaces where the *desire* of science to be both quantifiable and deterministic are actually compatible with the *nature* of that space (i.e., significantly knowable by reduction and quantification, such as astrophysics) are where technology finds an easy companionship. These sciences are often called the "hard" sciences: "hard" in the sense that they are readily described quantitatively and with predictability. They occur closer to the convergence of the axes that represent, respectively, increasing complexity (systems that show adaptation and unpredictability)

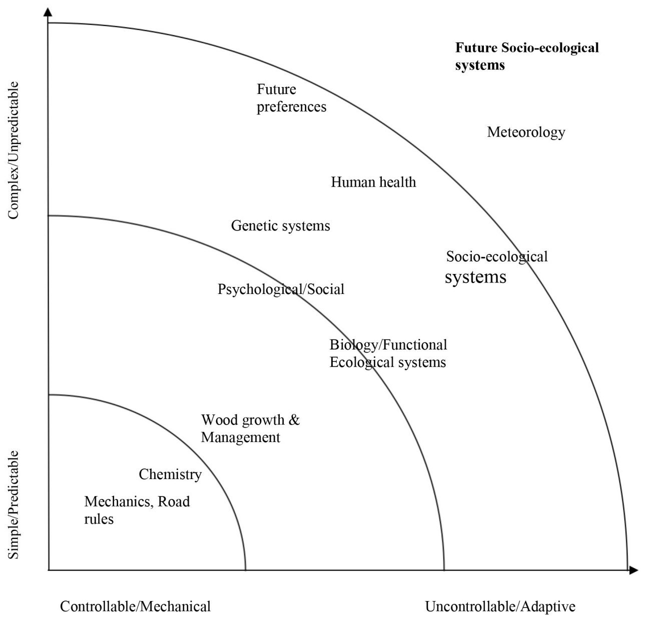

FIGURE 1 | Knowing the science-policy-operation: the limits of predictability and control.

and increasing uncontrollability (systems that are less amenable to human control).

Physics and chemistry are the archetypal hard sciences. Sociology is the archetypal "soft" science. It is "soft" in the sense that it is less amenable to quantification because it includes values that are not integral to an object, and involve aspects that are highly continent and variable. This makes the soft sciences the difficult ones.

For complex landscape and communities, research is better situated in the uncertain and uncontrollable space where there are fewer Newtonian regularities and many more contingent relationships.

From Hard Science to Complex Research

All sciences have a history, at some point or another, of trying to emulate the hard mechanics of physics and chemistry (even as physics moves beyond a Newtonian world view). An implicit Modern desire to find the elusive universal formulae from which certain and controllable prediction and world building will arise. And from there, the assumption is the wider whole could be built, one brick at a time. Never mind considering the concept of St Paul's as a pre-requisite to its attainment; the myth of the mechanical "System of the World" would provide.

Even some of the Humanities have that history – economics particularly. Ecology had that history, Though it has recently shifted from deterministic views of predictable paths to a "climax" "state of nature" to an appreciation of indeterminism, contingency, and complexity since the 1980's. That was after a longer period of internal dispute, and despite individual scientists arguing against determinism and "climax," such as Ed Ricketts from the 1930's (of *Cannery Row* fame) and Buzz Holling from the 1970's, both of whom had observed and witnessed fallsification of the grand theory and argued for that shift to complexity, adaptability, and indeterminism. For those thinkers, being in and of a place provided a wisdom that they ascribed to human intimacy far more than any ideal of dispassionate objectification.

From Agronomic Machines to Ecological Systems

Ecology is a key science of biological systems of the land, far more significant in breadth and depth of context than agronomy, which remains highly reductive and necessarily narrow of scope. Agronomy suffers from a situation where a certain statistical method drives the research questions (often small and not particularly exploratory) and reflects back on the researcher a convenient presumption of a Newtonian world view. This is problematic because it maintains rather than challenges that Modern worldview (or pretends it is not relevant). In Andrew Sayer's epistemological nexus of Worldview, Question, and Method as a reflexive system of research design, he argued that the *considered worldview* and the *relevance of the question* should drive the *research method*, and not the other way around (Sayer, 1984). Such a principle should particular be applied in the science dealing within a complex multifunctional multiply-connected space.

In matters of agronomy, the focus on breeding, inputs and yields of usually simplified systems gives statistical results. That is its field, somewhat divorced from the wider connected socio-ecological environment within which it lives or dies. That is perhaps the biggest mistake that many of the more technical disciplines have made: to presume that the methodologies that suit its substance – the science and technology relating to the physical management of growing a crop – are somehow suited to the far more complex and uncontrollable future and wider spatial world within which people of the land must adapt or fail. That highly subjective position, no matter how much it presumes to be objective and with high verisimilitude, will risk the creation and reinforcement of failures because its worldview may not match the real world or the issue at hand.

The systems multidiscipline, agro-ecology and socio-ecology, provide a context for research that is closer to reality.

REDEFINING SUSTAINABILITY AND THE PATHOLOGY OF RESOURCE MANAGEMENT

There is an implicit normative framework within all research ("What is it we ought to study?"). With regard to landscapes and communities, that "ought" is influenced by what we think is "sustainability." The definition of "sustainability" is highly dependent on our choice of "ontology" (the concepts, categories and relationships of and between things we unconsciously ignore or observe through our cultural "lens"), again – on the Modern machine or the complex systems worldview. Agricultural and environmental philosopher Thompson (1997, 2007) analysed the different worldviews in looking at what "sustainability" means to each. He distinguishes between sustainability defined by "Resource Sufficiency" of the mechanical paradigm (the sausage machine of life) and "Functional Integrity" – focused on the maintenance of environmental and social functions, within a system, in an uncertain world. Theories of "resilience" firmly rest in the latter systems worldview (Holling, 1973; Gunderson and Holling, 2002; Walker et al., 2004).

Such a systems world is defined, not by resource "nouns" but by processes, feedbacks and connections, analogous to "verbs" whose actions and participation vary with time, place and other factors. In combination and context, the "functional integrity" that keeps a system within some desired bounds can go awry through either human degradation of economic, environmental and social functions and connections, or through natural perturbation. Loss of "functional integrity" can create "vicious" positive feedback, tipping a socio-ecological system over a threshold to some future unpredictable state.

If we presume that a complex socio-ecological system can be simplified to a mechanical manifestation of the thoughts within a single science discipline, then the loss of key functions we are not aware of is more likely, and, with that, as is the degradation of socio-ecological function. It is thus more likely that a cascade of function loss will occur and a threshold event. Our whole evolutionary history has been dominated by surprise and the capacity or incapacity of any one species to adapt to change. Designing our landscapes as a simple "clone" perfectly "efficient" relative to this current state, in this one place and time, will lead to inevitable extinction. If there is any lesson from evolution, it is that.

The currently predominant industrial land use model emphasises the *Economies of Scale* of one thing. The rhetoric of "effective farm area" and emphasis on Gross Margin Analysis are consistent with that factory scale model. That emphasis reduces potential *Economies of Scope* that work with agro-ecological and socio-ecological functions for mutual economic, social and environmental gain. It also increases fragility, input dependency, reduces resilience and increases a potential threshold failure. The emphasis on industrial simplification and mechanical control leads to the increased chance of the system falling out of control. This is what Holling and Meffe (1996) defined as "the pathology of natural resource management": taking complex systems and seeing and then treating them through a Newtonian lens assuming reductionism, determinism, and controllability, resulting in management failure.

DECREASING RESILIENCE BY THE SIMPLIFICATION OF COMPLEX SYSTEMS: THE PADDY

Living within complex systems necessarily involves surprise, primarily because the integrated landscape and socialscape are complex and connected to multiple environments. Climate, markets, disease, labour issues, price and access to inputs, etc. are all subject to forces of change. Problems arise when we forget that complexity and unpredictability are inherently connected and when we presume that, by simplifying a complex system connected to multiple environments, we somehow magically remove all the unpredictability because it is easier to formulate in a model. It remains a "simple, complex system," but it is still complex.

When you simplify such a complex system, you maintain at least the same level of uncertainty as before but load that inherent uncertainty with a loss of redundancy and the exacerbation of potential cascade effects where one thing leads to another and another. You cannot simplify complexity away. The soils, crops, ecology, weather and climate, markets, and communities are still there. As it is complex, it will surprise, and because it is made simple, it will cascade with one thing leading to another through unpredictable pathways – known and analysable only after the event.

Despite this, we have unknowingly (or perhaps uncaringly) simplified our land-use systems through industrialisation, and the cascades have been evident. The loss of soil function is "solved" by a technological or energy input: more soluble fertiliser and irrigation. The loss of margin in the economies of scale commodity system is "solved" by aggregation, substitution of capital for labour, and migrant labour. The social cascade is "solved" by people shifting away and the biological cascade by more pesticide inputs. The hydrological soil-erosion cascade compensates with fertilisers and irrigation.

Vandana Shiva provided an example of simplified mechanical agronomy applied to a once complex socio-ecological space in her provocatively titled *Monocultures of the Mind* (Shiva, 1993).

The story she tells of the effect of the Green Revolution on the complex socio-ecological systems of Asian paddy-village life is now a classic within socio-ecological literature. The traditional system involves many different varieties of plants – both rice (up to 14 varieties) and others – to provide resilience against the uncertainties of climate and a better quality of diet. Uncertainty was the ruling paradigm, and reverence, diversity, resilience, and "minimising-the-minimum" was the traditional approach because failure means famine and death. In addition to the paddy rice, koi carp and ducks provide protein and keep insect pests and the mosquito larvae numbers down, so both human health and plant yield are improved. Vegetables from crop rotation, wild plants, and wild animals (including amphibians) supplement the diet. Seeds are saved and replanted. The system is not highly reliant on cash, and much of the system involves functional commons (Ostrom, 1990).

This was a self-organised, low input, and resilient socio-ecological system; it is not without research needs, but it can be far more readily disrupted if an industrial and narrow agronomic single-disciplinary approach predominates policy, unwittingly reducing the wider ago- ecological and socio-ecological system resilience.

But this came to pass. Into this complex system, narrow agronomy can significantly increase yields using diploid and haploid mule grains. People are persuaded perhaps because they do not imagine that one new input into the system will impact the resilience of their socio-ecological whole.

Ceteris paribus is the assumption that all else will stay the same, which, when you think of life as a system rather than a machine, never happens, especially in a multi-functional socio-ecological landscape.

Clearing a wetland or a forest does not *just* create more pasture. Cutting down a tree does not *just* stop stock from congregating under it. Changing from multiple fertile rice strains to one higher yielding mule strain does not *just* increase grain supply.

The consequences of any act roll out across multiple and long chains of cause and effect from ultimate cause to proximate cause and to symptom effect. But in Shiva's Green Revolution paddy-village example, with each new symptom the approach was not to go back and look at the integrity of the wider, deeper paddy-village (both agro-ecological and socio-ecological) system but to treat each new system effect, the symptom, with another techno-fix, creating a cascade of symptom to input to symptom and to input again.

The cascades ran through the social and the bio-physical. Farmers have to buy the grain, and cannot save it for next year, so need to develop a line of credit. The grain is indeed a heavy yielder, which means that crop rotations are not sufficient to maintain fertility. The solution for that symptom is to add fertiliser. But the effect of that is that the carp are not as happy, and so we have more mosquitoes. The techno-fix is an insecticide on credit. But that means the ducks are not doing so well anymore, thought the pesticide is dealing with the pests. However, the predator–prey balance is seriously off, so there is a need to buy yet more pesticides on credit because pest numbers have never been so high. Amphibian wild food is also suffering, and the free protein from koi, ducks, and amphibians is therefore depleted. On more credit, people can buy protein.

With all this building credit, the farming focuses on resilience and sufficiency whatever the weather to repay the creditor or risk losing the land. There is thus an increase in the planting of grain for market sale by stopping crop rotations. Because a rest from grain is no longer providing soil improvement or vegetables, the "solution" is to substitute practise for fertiliser input and to buy greens with more credit.

The creditor – usually the largest landowner in the village – forecloses on the debt of those smaller farmers who got into debt once again to buy more seed grain in the hope that next year the grain price will be higher so they can repay the debt. But, unfortunately, just as happened to the US Dustbowl farmers of the 1930's, the high grain production has led to a surplus and a lower price. The consequences include sale, despair, suicide, the exit from the land to swell the poor of the city, there to provide cheap labour.

Eventually, the larger landowner (or bank) is a lot bigger, while the socio-ecological system has collapsed despite GDP being praised; as this is the chosen metric when so many of the system failures are not quantifiable, or are particular to place, governments keep investing in the failure.

The Thoughtscape Derives the Landscape: the Context Changes While the Song Remains the Same

These are only some of the system effects. There are other potential downstream ecological, resource depletion, psychological, sociological, and political effects. That is why an analytical Newtonian reductionism is questionable without a wider systems context to guide the emphasis of research, policy, and practise. That is how connected are our landscapes. How we think of them – our thoughtscapes – would appear to matter.

The change witnessed above took a previous self-organised, low-input, resilient agro-ecosystem and a socio-ecological system and turned them – through the thoughts and worldview of the advisors – into the factory image they saw in their heads. This is no "objective" research space, made far worse by neither acknowledging that a worldview exists nor considering the wider systems effects, feedback, and thresholds beyond their statistical agronomy.

This paddy example represents an analogy of change for the complex, multi-dimensional, and adaptive socio-ecological land-use systems of many countries, including New Zealand pastoral agriculture. Loss of system function, economic marginalisation, aggregation, and out-of-local displacement of ownership and, with it, the degradation of local economic multipliers, social decline, and the degradation and loss of environmental functions lead to dependency and loss of well-being.

The cascades lead not just to increased fragility, each decade more difficult to escape, but also to a curious stridency of defence of the prevailing *Habitus*: "This is what we do."

The particular root cause practise will differ and the local context shift, but there is a sociological and psychological cause that lies consistently beneath it all, and that is the industrial lens through which we are taught and teach, and this is reinforced through much research, policies, and commercial messaging.

However, alternatives that emphasise the reality of complex place-based agro-ecological and socio-ecological systems are emerging in increasing strength, not because the ideas being presented by these researchers and practitioners are new (they are not) but because the current industrially- predominant paradigm is increasingly indefensible.

HISTORICAL PATTERNS, CHALLENGES, AND ALTERNATIVES

Challenging the current industrial-mechanical paradigm requires some understanding of its history, especially with the rise of inputs and *economies of scale* over the more traditional *economies of scope* approach that emphasised maintaining a coherent system without the need for expensive inputs. That paradigm shift was never uncontested, and that challenge has become more immediate and far wider in scope with time.

In the 1940's, Sir Alfred Howard contrasted traditional farming systems particularly in Asia with the emerging chemical fertiliser revolution that treated soils more as a physical and chemical hydroponic medium than an biophysical ecosystem (Howard, 1943). America had a number of proponents for treating the land as a system, with better yields, lower inputs, fewer pest control problems, and a better local economy, social, and environmental values. Both Faulkner (1945) and Bromfield (1945) wrote from their personal experience. $N = 1$ case studies can provide exemplars of the extraordinary; opening our eyes to what we could have, and be. They also wrote from a perspective where humans are part of the greater system, and touch on philosophy.

The philosophy challenging Modernity paralleled these biophysical exemplars. Leopold (1947) led the way to an integrated world view with *A Sand County Almanac*, at least in the twentieth century. Carsen (1962) responded to the first real consequence of industrial land use with *Silent Spring*. The consequences to biodiversity sat alongside a crisis of farm economics. Their challenges were ethical as much as metaphysical.

The cycles of accelerating landscape dysfunction were the focus of Willard Cochrane's technology treadmill metaphor. In 1958, he defined the challenge of continued economic marginalisation resulting from a vicious cycle of increasing production, reducing real prices, reducing cost through scale and yet more land-owner aggregation, technofix industrialism, and social and worker marginalisation (defined in the industrial model as "human resources") *ad absurdum* (Cochrane, 2003). The process involved different details, but the same general direction of serious family farm crises as Vandana Shiva's paddy example. An absurd process to which asystematic, non-synthesised analytical thinking is blind.

Few were listening to these commentators on what was happening to the functional health of the wider landscape system in either America, New Zealand, or beyond. The 1970's brought the call to industrialise further. "*Get big or get out*," and "*Plant fencerow to fencerow*" was the call of the US Department of Agriculture Secretary Earl Butz. Berry (1977) wrote his classic *The Unsettling of America* in response, lamenting the industrial effects on communities, families, local economies and the land, and calling it a "crisis of agriculture" derived from a "crisis of culture," of thought, and of worldview.

Agro-ecology emerged in the 1980's as some academics saw the broader issues and the social, environmental, and economic thresholds becoming uncomfortably evident. They were intent on looking at science-based alternatives. Altieri (1983) was followed by researchers looking at the potential to work with rather than against the environment and enhance productivity through within- and between-patch polycultures, and through a far stronger emphasis on the less well-studied soil ecology (perhaps because it is both microscopic in scale and so context-dependent) and soil functional links with animals and grazing management.

Ecological approaches to land use as a challenge to a failing industrial paradigm has only expanded since those early endeavours to solve the problems of industrialism, from Jackson (1980) to work by Jeffrey McNeely and Sara Scherr (McNeely and Scherr, 2003; Scherr and McNeely, 2012). The academic research and literature associated with agro-ecology are now considered. The names proliferate, from regenerative agriculture to eco-agriculture to permaculture, but their essence derives from an agro-ecological rather than an industrial perspective.

Novelists joined in to highlight the moral questions and the loss of values for the benefit of a few, particularly Smiley (1991) and Proulx (2002). Rural Sociology provided an increasing examination of the social and economic consequences to farming families and communities of this policy shift to growing industrial intensification [for example, Bell (2004)].

The New Zealand Parliamentary Commission for the Environment directly challenged the need for a "redesign" of agriculture in 2004 Parliamentary Commission for the Environment (2004). The result was a resounding dismissal from policy makers to the New Zealand farmers' union Federated Farmers.

From the late 2000's, international reports began to emerge, the most significant being UN Special Rapporteur on the Right to Food de Schutter (2011) report to the 2010 General Assembly, which included this statement:

> *"Based on an extensive review of recent scientific literature, the report demonstratesthat agroecology, if sufficiently supported, can double food production in entire regions within 10 years while mitigating climate change and alleviating rural poverty. The report therefore calls States for a fundamental shift towards agro-ecology as a way for countries to feed themselves while addressing climate and poverty challenges."*

The evidence de Schutter accumulated, which has been expanded upon in the years since, is clear. The industrial approach to landscapes that treats land as a factory, simplified to suit the mass production of undifferentiated commodity at low cost using high-energy inputs, is unquestionably contributing to significant and planet-threatening environmental problems in the areas of water, soil, biodiversity, and the atmosphere as well as social and economic problems.

The solutions are to see and think about landscapes differently.

SPATIAL AGRO-ECOLOGY: THE POTENTIAL THAT LIES WITHIN MULTI-FUNCTIONAL INTEGRATED AND PATTERNED LANDSCAPES

Reimagining landscapes as complex adaptive systems is both socio-ecological and agro-ecological. At the core of agro-ecological thinking is the concept that both biophysical elements (soils, soil ecology, animals, vegetation land covers, water and its function, microclimates, etc.) and land cover patterns can provide mutual and multiple benefits in a designed and managed land system. Those patterns are premised on both the natural variations within a landscape and the connections between and within elements and patches with potential for synergies (landscape mutualism).

Land cover patches include pastures, crops, woodlands, wetlands, tall herbaceous leys, etc. This is a polycultural world with heterogeneity both between and within land cover patches at its core.

The industrial factory view of landscapes works directly against pattern and potential landscape mutualism. It forces the land into a homogeneous uniformity, marching in step whatever the limits and potentials of the terrain. The consequence is dysfunction, an increase in inputs of energy and work in order to keep the ideal of the machine far away from anything remotely like a natural patterned and dynamic system.

The classic New Zealand pastoral example involves those farm areas that are dysfunctional in pasture but beneficial in other land covers, historically cleared of functional woodlands and functional wetlands in order to create a never-ending problem pasture. Many of these areas are at the poorer end of pastoral potential, representing <10% of the production from the best pastoral areas (Dr. Gordon Cossens, *pers. comm.* Ken Stephens, *pers. Comm.*).

That variation in the patterns of production and stock preference is made more complex with the coinciding patterns of real costs. Poor pastoral production is often combined with directly associated threats to the loss of environmental function of value to farm resilience and reliance on inputs: soil degradation, the degradation of both water retention and quality, the degradation of stream systems. Combined with those production and environmental patterns are 80:20 principles of financial costs: stock losses, mustering problems, ineffective returns to fertiliser, high costs in chemical weed control, and repairs and maintenance common to steeper country.

Some attributes – low return, high environmental risk and sensitivity, and high costs – are very often combined. Steep dissected gullies, often the first to revert and avoided by stock, are classic sites. The agricultural emphasis is to clear and put in pasture in the interests of scale (and an unrealistic understanding of the landscape system). Many farmers ignore that "advice" and integrate woodlands into their landscape design. Their real success is neither understood nor embraced by single- discipline pastoralists in research, education, policy, or advice.

The Farm Systems Logic of Spatial Integration of Diverse Land Covers

Many of these high costs are, for accounting convenience, considered "overheads" – woody weed control, labour, etc. – when they are actually direct costs that are difficult (and usually unnecessary) to measure. Costs in these areas are either not counted at all (in the case of soil, water, and biodiversity function) or are assumed to be general – as if the land was a uniform factory rather than a patterned landscape.

The accounting convenience then reflexively morphs back into an unquestioned generalisation in the minds of pastoral analysts. Pastoral agronomists considering whether another land cover, such as woodlands or wetlands, might be better or worse for the whole farm in any particular area fall back into the factory fallacy, the repeated messages from active farm foresters notwithstanding. They consistently make at least five errors, which a socio-ecological and agro-ecological worldview will not.

1. They use average production data rather than actual data from low production areas: so a 2 stock unit/ha (s.u./ha) is presumed to represent the average of 12 s.u./ha, and another non-pasture landcover will involve that incorrect loss of revenue.
2. They forget that the category of overhead cost is a convenience and then misrepresent the 80:20 landscape cost patterns for weed control etc., assuming therefore that another non-pasture landcover will involve no cost decrease.
3. There is no consideration given to agro-ecological system effects like animal shelter, shade, any edge browse designs, soil erosion loss, hydrological function, water quality that feeds into stock water and stock health, evapotranspiration reduction etc. A factory does not exhibit system effects because it is not perceived as a system.
4. There is no consideration given to option value from diversity, and the potential emergence of either another source of revenue, cost reduction, ecological function, or input substitution.
5. There is no consideration of the significant social values associated with beauty and living within a highly functional landscape (you can make no apology for the inclusion of this point when you talk with farmers about being on the existential edge and who credit the beauty of their landscape, woodlands, and streams with their return to emotional health).

The general answer from the factory world view is "Don't diversify land covers because you'll lose revenue and you'll have to service the unchanged overheads with that lower revenue." It is false because of the analytical framing and the industrial metaphysics they employ. Just one example of the scope of potential in landscapes not realised because the system is reduced to a simpler worldview.

In direct contrast, agro-ecology designs from within an understanding of the wider system, for multiple gains across economy, society, and environment. It dances with the land and rejoices in the patterns of variation and connection. Agro-ecological design is effectively a process of creating a "self-organised system" where the system runs without continued energy input, without negative environmental outputs, and with social, resilient, and economic benefits. The soil health, permanently flowing streams, water infiltration and holding, water quality, stock health, resilience, low input, carbon-neutral, community-friendly, profitable, productive, financially efficient, and high -value produce characteristics all go hand in hand.

RESILIENCE TO DROUGHT

A key landscape system function relates to the threats of drought and flood. One drought crisis occurred between 2008 and 2010 in the rain shadow east coast of New Zealand. The system effects on land, animals, and farming families were considerable though unquantifiable in any general sense. Suicides occurred.

The response was interesting as a sociological study in itself. The approach from most agricultural consultant technocrats was not to look at the land function and capacities as relevant to a solution. The land was fixed: an immutable machine. Drought was simply the absence of rain as an essential (quasi-hydroponic) input into the mechanism. The solutions were to destock early, wait for rain, and use the occasion to advocate for large-scale irrigation schemes as the technofix solution. Most of the researchers, policy people, and consultants only spoke that language: land as a fixed factory of mechanical parts, inputs, and outputs.

A few of us came in with a question; "What is a drought?" and discussed how the lack of landscape capacity to infiltrate, hold, distribute, reduce evapotranspiration, and access deep soil water meant you could have a drought in the afternoon following a 25 mm rainfall event.

We then started discussing the first principle system capacities within the landscape, relating to soil quality, vegetation, stock management, and landscape water bodies in particular.

The degradation and restoration of landscape systems is well-documented in the eye-witness case study literature and the research. Seeing land as a factory, leading to the reduction of hydrological capacities, impacts not just the lack of resilience to flood and drought but also economic options and community well-being. That cause of degradation is associated, if not directly caused by, seeing land in an input-output mechanical sense, rather than an integrated agro-ecological and socio-ecological system.

The Modern "solutions" are then posited from exactly the same mechanical world view: large centralised dams and irrigation systems. As the shift into systems thinking occurs, it is both the "Third world" countries and those with strong previous and current indigenous practise (and worldview) that are now focusing more on local system hydrological functions (Pearce, 2006; Pretty, 2007; Lancaster, 2013; Nabhan, 2013; Subramanian, 2015).

The local case study by Coller (1959), set in a tributary of the Frazer River in British Columbia, is a case in point. The loss of the landscape systems capacity to hold water, primarily through the loss of beaver dams, led not only to the loss of local scale agricultural irrigation downstream but also to the loss of a fur-hunting livelihood for the local communities. The whole socio-ecological landscape system had been degraded from effectively a sponge with permanently flowing streams and mutualist economic options to a hard plate boom and bust hydrological pattern and mutual losses to the environment, economy, community, and general resilience. The restoration of a keystone landscape function, and with it the retention of the potential energy of water in the landscape, led to multiple positive outcomes because multiple connection and potential mutualism (rather than always assuming Cartesian tradeoffs) is the nature of complex socio-ecological and agro-ecological systems.

MARKET VALUE CHAINS AND AGRICULTURAL STRATEGIES – INDUSTRIAL COMMODITY FAILURES AND ALTERNATIVES

Reimagining landscapes is strongly associated with the broader primary sector strategies adopted by any country. In broad terms, there are two competing sets of strategies.

1. The Industrial Strategy: the high production of low-cost undifferentiated homogeneous commodities. Landscapes, people, and animals are treated as factory units and inputs with a focus on engineered economies of scale. Primary commodities are sold through short value chains to centralised continuous processing, focusing on economies of scale. This is both the historic colonial model and the agribusiness corporate model.
2. The Diverse Value Strategy: the production of diverse, functionally sustainable, high-quality produce. Landscape, people, and animals are treated as parts of a functioning whole whose functions, patterns, and connections provide the "economies of scope" opportunity for a number of mutual positives, particularly potential cost reduction, revenue option, environmental health, multiple community value chains, and the marketing narrative to retain price position as a price maker, and avoid Cochrane's technology treadmill. Primary production is sold through longer value chains or as direct as possible to end consumers, bypassing middlemen. Processing is more localised and batch processed to maintain a focus on quality and differentiation. This is the emerging strategy geared to suit consumer mega-trends of safe, quality, and sustainable produce with a narrative. The emergence of batch-brewed boutique breweries as an alternative to low-value continuous processed beer is a comparative analogy.

The Industrial Strategy has dominated in New Zealand and much of the once colonial world since the days of European settlement. The energy intensification of land, while retaining a focus on undifferentiated commodities is directly linked with the degradation of rural socio-ecological systems. The explanatory dynamic that lies beneath the degradation of social and environmental function is Cochrane's Technology Treadmill: a repetitive cycle of financial marginalisation and increased industrialism.

The cycle starts with a poor, commodity "price taking" market position, leading to various responses that make the situation worse in the medium and long term. The reality of reduced real agricultural prices that occurred throughout the twentieth Century is connected to this dynamic. The logical response to a lower price is, theoretically, to shift production to an alternative, the negative price-production feedback dance of orthodox economics. However, when there is no alternative because there is no other option, then a commodity lock-in trap occurs. In effect, the focus on commodity "cost efficiency" or gross production of a singular production is the catalyst for the system's demise. Options are lost. The perfect engineered "clone" for these perfect current conditions is more vulnerable to any future change in cost, price, or availability of any supply made critically because of the increasing linearity of the production "line".

The solution within the Industrial Strategy is to continue doing exactly the same "this is what we do" *Habitus* within colonial and agribusiness commodity land use. Without a production alternative, the first option for a now financially marginal operation within that *Habitus* is to increase the economies of scale of the operation, retaining the cost-efficiency focus. Farms aggregate, conglomerate, and eventually corporatise with ownership absent and their multiplying expenditure no longer circulating locally. The second is to cut costs further by substituting capital for labour, and migrant labour for local labour, and pushing costs out beyond the horizon to debt, community, or environment. The third is to be swayed by new technology as a hopeful saviour – another increase in inputs.

The consequence of each of these steps in improving "cost efficiency" and therefore a temporary margin, is for the stronger buyer of commodities to then decrease prices again. And so within that industrial system, the treadmill continues. Usually, the responses are the same for each iteration of the treadmill. As with drought, the presumption within a Newtonian worldview is that the financial situation is outside their influence. It is what it is: wait – and hope – for rain or a price rise.

This production-market system is another complex adaptive system, very much part of the wider socio-ecological system of the farm and landscape enterprise. Synthesis is what allows policy and research to see the feedbacks, policies, and research needs, not analysis outside any such wider systems context, such as only examining short-term supply and demand production data. This is particularly the case where research looks to ease of quantitative data gathering, or amenability to statistical analysis, rather than what is a more important question however challenging that may be to both the mechanical worldview and preferred method. Some questions are not asked. And the world view and method are not questioned. The lock-in trap of the industrial mindset is as evident within the professions as within real practise in the field.

Cochrane himself, while recognising the treadmill, argued what was effectively another industrial Response: to cap supply (the previous strategy during the Great Depression). However, price is not just a function of supply–demand quantification. Price relates to power differentials between buyer and seller, for example on wage worker on one side of the desk and seven corporate lawyers on the other. Relative supply and demand are but one factor in that power differential. A farmer and a megacorporate buyer are not of equal power whatever the supply and demand situation.

Socio-ecological and agro-ecological systems thinkers propose an alternative. A shift in worldview and *Habitus*. At root are two things. First, the necessity to focus on price retention and therefore product narrative for the end consumer so that any efficiency gain is retained by the grower and not taken by the buyer. The second is to work with the scope of potential of the agro-ecological and socio-ecological systems, that is, to shift from an industrial factory cost-efficiency "economies of scale" focus to a system resilience "economies of scope" focus. From this, we see the emergence of the Diverse Value Strategy.

WHERE TO GO FROM HERE

Wendell Berry was right in defining the crisis of agriculture in the 1970's as a crisis of culture. The crisis extends across land use, and has only exacerbated; fewer family farms, poorer communities, threatened environments. The solutions to date have retained the Modern Industrial worldview as their underlying thoughtscape. We have simply moved from colonial commodity industrialism to agribusiness corporate industrialism. This mechanical metaphysic is the water within which we swim without really recognising it or even thinking about it. The factory model still predominates in practise, policy, advice, research, and education as a self-perpetuating *Habitus* of the status quo. We are taught, we research, we teach, we make policies, we advise, and the next generation continues. This is how we think of the world, and "this is what we do."

For someone educated in science, it is difficult to even listen to the idea that the solutions to our land use and rural community crises are not related to another technology or discovery but to an idea we may have in our heads. It is far more difficult to acknowledge those ideas. It is far more difficult again to think about them. It is more difficult again to change them. We are not taught that we even have them.

A fundamental change to an agro-ecological and socio-ecological systems view is yet to occur. Agro- ecological thinkers remain marginalised, at least in New Zealand. Modern ideas that dominate land-use minds, ironically considered value-free, are deeply embedded within our culture of land use, perhaps more in the academic, policy, and commerce vocations than the field. It is questionable whether farmers are once again leading the way with the slower inertia of the bureaucracies following.

Notwithstanding the inertia of the industrial mindset, there is such potential in reimagining and redesigning a post-industrial landscape, that its own inertia will inevitably build. The paradigm shifts of the past have often been rapid.

It is neither the logic nor the coherence or the field exemplars that are missing. It may take a single outside event to change: a single reformation moment.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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REVIEW
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Grazing Into the Anthropocene *or* Back to the Future?

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This essay examines three central components of extensive livestock production—herd composition, grazing/pasture management, and rangeland tenure. In all of these areas, fenced, and open-range forms of migratory pastoralism face a number of shared problems. Set aside the presumption that either one of these systems is technically or institutionally more advanced than the other, and it turns out that each has lessons for the other. 1. For a variety of reasons, including climate change, we can look forward to a future world with less grass, which presents a challenge for livestock producers reliant on grass feeding livestock. With little delay and minimal scientific support, East African pastoralists are already adjusting to a new woody world by diversifying the species composition of their herds to include more browsers—camels and goats. There is a potential lesson here for commercial ranchers who have traded the stability of mixed herds for the profitability of keeping sheep or cattle alone. 2. Migratory rangeland systems distribute livestock very differently than fenced, rotational systems of livestock, and pasture management. Whereas, migratory herds exploit environmental heterogeneity, fenced ranching attempts to suppress it. Emerging archaeological evidence is demonstrating that pastoralists have amplified rangeland heterogeneity for millennia; ecological research shows that this heterogeneity sustains both plant and wildlife biodiversity at the landscape scale; and new approaches to ranch management are appropriating aspects of migratory herding for use on fenced ranches. A rapprochement between the environmental sciences, ranching, and open-range migratory pastoralism has occurred and merits wider policy recognition. 3. In contemporary Africa, indigenous tenure regimes that sustain open rangelands are eroding under pressure from market penetration and state encapsulation. At the same time in the American West, there are emerging novel land tenure instruments that replicate some of the most important functional characteristics of tenure arrangements in pastoral Africa. After many false starts, it appears that some aspects of American ranching do provide an appropriate model for the preservation of the open-range migratory systems that they were once supposed to supplant. "Development" policy needs to reflect upon this inversion of roles and its implications for accommodating diversity.

Keywords: pastoralism, ranching, herd composition, migration, rangeland tenure

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INTRODUCTION

This article is built around the distinction between the Neo-Anthropocene and the Paleo-Anthropocene (Erlandson and Braje, 2013; Foley et al., 2013). The Neo-Anthropocene came into existence around 1800, with the birth of industrial capitalism. Many of the people contributing to this book represent extensive livestock systems that were invented in response to the Neo-Anthropocene. As the organizers of this collection clearly recognize, observers of these systems are now trying to think themselves out of some of the boxes that they find themselves in[1]. Social anthropology in the twentieth century, and archaeology in the twenty-first century, offer an insight into alternative kinds of extensive livestock production systems, those of the Paleo-Anthropocene. These systems were remarkably resilient for nearly 10,000 years. What do they tell us about how to survive?

I will argue that these pre-industrial systems of livestock production do not offer us literal models of how to reconstruct industrial livestock production; the Neo-Anthropocene has rendered them inoperative. Especially for those of us accustomed to the comforts of consumer capitalism, they are good to think, not good to live. But we can identify the principal characteristics of these systems, identify the ways in which they differ from commercial ranching, and explore the implications of these differences. Broadly speaking there are three differences—their economy, the nature of their political organization and the source of energy that powered these societies. These were self-provisioning and redistributive economies in the main. Households produced for themselves and surpluses tended to circulate locally, often in the interests of maintaining local political institutions. Local-level politics was important because rural communities were frequently autonomous and sovereign, and their political integrity was essential to their control of vital natural resources. Finally, the power that drove these economies and societies was human labor and animal energy. Everywhere on the globe these features of Paleo-Anthropocene livestock production are eroding with expanding state power, commodification, privatization, and the substitution of industrial inputs for human labor and animal energy. It's called development, and there's no going back, but it is possible that pastoral systems that remind us of our past may provide a useful platform for thinking creatively about our future. This paper examines that possibility.

To begin we must level the playing field. By this I mean that we must, from the perspective of the Neo-Anthropocene, establish some basis for respecting Paleo-Anthropocene forms of extensive livestock production. **Table 1** does this, albeit crudely. It shows that in some sense African open-range livestock production in the twentieth century was more productive—often by several multiples—than contemporaneous forms of commercial ranching operating under comparable ecological conditions. The qualifier "in some sense" is important here. **Table 1** engages in the denominator game; its results are startling because it expresses output per unit land area. If output is expressed per head of livestock or per unit of human labor the results are very different and in conformity with conventional expectations—commercial ranching wins every time. For example, referencing data on African and Australia ranching in the 1970s, Jahnke estimated that "Labour productivity [of open-range pastoralism] is in the order of $50 [USD] per man instead of over a thousand or thousands in ranching. Labour productivity in pastoral systems is therefore very low, or to put it the other way around, pastoral systems are labour-intensive; they have a high employment capacity at low levels of renumeration" (Jahnke, 1982, p. 87). Cattle weights are a convenient measure of per capita livestock output and these indicate that ranching is also more productive per animal than pastoralism. Across sub-Saharan Africa as a whole, Otte and Chilonda (2002) estimated that semi-arid pastoral cattle weighed on average 61–66% of semi-arid ranched cattle, which is broadly in agreement with available country-level data. For example, communal (open range) Nguni cattle weighed 66–70% of commercial breeds raised on private ranches in South Africa (Strydom, 2008; Strydom et al., 2008). In Botswana in the 1970s, cattle kept at unfenced boreholes weighed 75% (Rennie et al., 1977) to 81–82% (Animal Production Research Unit, 1979) compared to cattle kept on freehold ranches. According to Cossins (1985) pastoral Borana cattle kept in Ethiopia weighed 54–87% of Borana cattle kept on Kenya ranches in comparable environments.

TABLE 1 | Relative productivity of commercial ranching and open-range pastoralism under comparable ecological conditions.

Country	Pastoral vs. ranch productivity *(Ranching = 100%)*	Units of measure
Mali	80–1,066% (relative to United States)	Kg protein production/ha/year
	100–800% (relative to Australia)	Kg protein production/ha/year
Ethiopia (Borana)	157% (relative to East Africa)	MJ/ha/year of gross energy edible to humans
Kenya (Maasai)	185% (relative to East Africa)	Kg protein production/ha/year
Botswana	188% (relative to Botswana)	Kg protein production/ha/year
Zimbabwe	150% (relative to Zimbabwe)	$Z/ha/year
Uganda	667% (relative to Uganda)	Ug. Shillings/ha/year

Sources: Mali: Penning de Vries and Djiteye (1982); Ethiopia: Cossins (1985); Kenya: Western (1982); Botswana: De Ridder and Wagenaar (1984); Zimbabwe: Barrett (1992); Uganda: Ocaido et al. (2009).

I conclude that both commercial ranching and open-range pastoralism are productive, but in different ways. To understand why they are so different we can begin by examining the factors of production that underpin each system. The regions of semi-arid Africa inhabited by indigenous African pastoralists are relatively densely settled compared to areas dominated by Euro-American forms of commercial ranching predicated on the extirpation of indigenous populations. As a consequence, in pastoral Africa land is valuable whereas labor is abundant

[1]A paper that focuses largely on intensive systems of livestock production, concludes that "In short, there is little or no scientific consensus on the sustainability of trajectories of various livestock production systems" (Tomich et al., 2011, p. 204).

and cheap, relative to commercial ranching areas. As a result of their relatively high population levels, African pastoralists need to squeeze every bit of value out of the natural resources that they control, and they have abundant supplies of labor to devote to this effort. **Table 1** suggests that they are successful—on their terms. Commercial ranchers operate under very different conditions and with very different results. Labor is expensive because ranchers must compete for it against other sectors of the economies of industrialized nations. To do this they commonly replace human labor with hydrocarbons and a variety of industrial inputs the manufacture of which is ultimately based on the consumption of hydrocarbons: "In a broad sense, the intensive use of chemical inputs and fossil energy can be viewed as substitution of petroleum and natural gas for ecological functions and labor" (Tomich et al., 2011, p. 199)[2].

Is this beginning to sound at least a little bit interesting—a productive form of extensive livestock production predicated on minimal hydrocarbon consumption and offering abundant job opportunities? Alas, there are snags. The abundant job opportunities come with low wages and difficult working conditions. High levels of output are also predicted on the self-provisioning aspects—home production for local consumption—of these partially self-sufficing economies. Self-provisioning means that consumers are permanently on hand to use a wide variety of livestock goods and services—meat and dairy products certainly, but also—depending on the society and environmental setting—dung, urine, transport and traction, blood, bones, hides, and hair—almost everything an animal has to offer. Some part of the high output of pastoral herds must be attributed to the wide spectrum of both live-animal and terminal products that are harvested from them. With market exposure much of this complexity falls away as managers focus their attention on marketable commodities and abandon the production of goods and services that are now superfluous or may even interfere with efficient commodity production[3]. This narrowing process has been repeated time and again in twentieth century pastoral Africa and I suggest that it is a near universal concomitant of increased market involvement. To the extent that capitalism is part of our future, the self-provisioning, broad-spectrum productivity of pastoral herds is probably not a relevant model, except for devotees of self-sufficiency who wish to disengage from market-based consumerism.

More relevant are the production systems and husbandry practices used by open-range pastoralists. At least three aspects of pastoral husbandry should be of interest to other types of contemporary extensive livestock producers. These are:

- The maintenance of herds composed of multiple livestock species, and in particular, the frequent mixing of large- and small-bodied browsers and grazers—cattle, camels, sheep, and goats;
- The way open-range producers exploit and amplify environmental heterogeneity through their herding practices.
- The institutional arrangements pertaining to resource control/access/ownership that facilitate the free movement of livestock at the landscape scale.

This paper will examine each of these possibilities.

THE MIXED SPECIES COMPOSITION OF PASTORAL HERDS

We can begin with an abiding challenge of our time—global environmental and climate change.

There is robust evidence of shrub encroachment on a global scale in arid environments and on a regional scale in semi-arid areas including parts of the western USA, Australia, Africa, and South America (Van Auken, 2000, 2009; Andela et al., 2013; O'Connor et al., 2014; Stevens et al., 2017). In addition to local land use and ecological variables—e.g., grazing intensity, fire regime, soil and vegetation characteristics—global climate change, and in particular the frequency of large precipitation events (Schwinning and Sala, 2004), and enhanced levels of atmospheric carbon dioxide, are almost certainly implicated in these trends: ". . .. It is likely that shrub encroachment will be augmented in the future, even if other factors known to promote this land-cover change (e.g., grazing) are reduced" (Maestre et al., 2012, p. 3,065).

As elsewhere, bush encroachment is widespread in East Africa. East Africa has also experienced a three- to four-decade-long trend of declining rainfall in pastoral areas of eastern and southern Ethiopia, Somalia, and parts of semi-arid Kenya (Pricope et al., 2013; López-Carr et al., 2014). It is instructive to consider how livestock producers in these areas have coped with the dual challenges of aridification and bush encroachment.

One component of their response has been an increase the proportion of both large and small-bodied browsing species—camels and goats—in pastoral herds. This response has built on the pre-existing species diversity of East African herds. Pastoralists kept multiple species in order to exploit diverse grazing environments and to provide a variety of products for direct household consumption. Cattle were valued for the volume of milk they produced, for instance, while camels were valued for their capacity to give at least some milk in a drought. Small stock were kept for routine domestic meat consumption or for sale to meet small expenses. Because goats could rapidly multiply, pastoralists often used goats to rebuild their herds in the recovery years following a drought.

As late as the 1960s, however, herding societies in East Africa could be divided roughly into two groups based on the species composition of their herds—the cattle specialists

[2] Range science has a long history of encouraging these substitutions. Early North American range science promoted the systematic extermination of organisms that interfered with the maximization of livestock output and the minimalization of labour costs. Predator control achieved these objectives by allowing livestock to roam freely without supervision and without being eaten by anything other than humans. Fencing, it was argued, reinforced the benefits of predator control by eliminating herding and driving, which saved labour and also encouraged livestock to scatter more evenly, thereby diminishing their impact on pastures and increasing their productivity (Sayre, 2017, citing early twentieth century US government-sponsored range research).

[3] As the term is used in this paper, a commodity is a good or service that can be readily exchanged in a market because it is broadly equivalent to other items of the same type.

vs. those who kept herds with a more diverse mix of species. Archetypal cattle keepers included the Maasai of Kenya/Tanzania (Jacobs, 1975; Galaty, 1982), the Borana of Ethiopia/Kenya (Dahl, 1979a,b), and the Pokot of Uganda/Kenya (Österle, 2008). Alternatively, the Turkana of Kenya (Coughenour et al., 1985) and the Karamajong of Uganda (Dyson-Hudson and Dyson-Hudson, 1969) exemplified the mixed species option, keeping as many as five types of livestock—cattle, camels, sheep, goats and donkeys—and selling, slaughtering, bleeding and milking all five species. Broadly speaking, the cattle specialists occupied the better-watered grasslands of the region, while mixed herds were located in more the arid areas and tended to rely for their forage on a combination of grazing and browsing.

Declining precipitation, increased frequency of drought, bush encroachment and reduced grassland cover and species diversity have in recent decades undermined the viability of cattle pastoralism and increased the attractiveness of livestock species that are recognized by pastoralists as better adapted to their changing environment (Megersa et al., 2013, 2014). The diversification of the herds kept by what were once iconic cattle-owning peoples is now well-documented.

- At one Maasai Group Ranch in Laikipia, Kenya, in 1980 there were no camels; by 2015 at the same ranch 10% of all households owned camels (Volpato and King, 2019). In all of Mukogodo Division of Laikipia District in Kenya in 1983 there were 254 camels; by 1998 there were 3,500—a more than 1,200% increase. Over the same period, the traditional cattle-dominated herds of the Mukogodo Maasai were being replaced by sheep and goat-dominated herds (Huho et al., 2011).
- In East Pokot, Kenya, the estimated maximum number of camels in the 1980s was 3,500 head; by 2011 the number had increased more than twofold to 9,600 (Bollig, 1992, 2016). Long-time observers of this area agree that, "… small stock numbers have hugely increased" (Bollig, 2016; Vehrs, 2016). In a paper entitled "From Cattle to Goats," Österle argues that the East Pokot cattle herd oscillated around 100,000 head from 1920 to 2005, while the goat herd increased more than fivefold over the same period (Österle, 2008).
- Since the 1980s, the Ethiopian Borana of Yabello and Dire districts have doubled the contribution of sheep and goats to the composition of their livestock holdings (Cossins and Upton, 1987; Megersa et al., 2013) and involvement in camel keeping has expanded from 6% of households in 1980 to 40% in 2011 (Megersa et al., 2013). Wako et al. (2017) also report the expansion of camel husbandry in Yabello District. In northern Kenya, the Borana of Isiolo County have recently diversified their livestock holdings such that more than 40% of households now own camels (Kagunyu and Wanjohi, 2014). In nearby Marsabit County, by 2012 camels were being kept at higher altitudes by people who rarely kept camels in 2000 (Watson et al., 2016).

National statistics on livestock numbers in Kenya confirm the generality of these trends. Since the 1970s, the national cattle herd has more than doubled growing by 113%, but camel numbers have expanded by 574%, goat numbers by 483%, and sheep by 381% (FAO STAT). Though less clear-cut, global trends reflect developments in Kenya. Since 1980, global sheep numbers have been largely stable (up by 9%) and cattle numbers have expanded modestly (+23%) while goat populations have more than doubled (+123%), led by Africa (+200%) (FAOSTAT[4]). FAO data on world-wide camel populations are incomplete and unreliable, but a comprehensive review suggests that:

> Between 1961 and 2018, the world camel population was multiplied by 2.75, a higher value than equines (1.06), sheep (1.21), cattle (1.58), small camelids (1.72) and buffalo (2.33). Only the growth of goat population appears higher (3.00). Such development testifies to the impact of climatic changes marked by widespread desertification of vast stretches of land in the world and of the renewed interest in the camel within this new global climatic context. It also highlights the growing interest for camel products (Faye, 2020).

Estell et al. (2012) correctly anticipate a future "world with less grass": "Grasslands are in decline (a trend expected to continue) for a number of reasons (e.g., competing land uses, urban sprawl, and invasive species), though two dominant factors are conversion to cropland and woody plant encroachment" (Estell et al., 2012, p. 553). They have recommended a range of science-based responses including genetics and selection, detoxification, dietary supplementation, and behavioral modification to enhance the ability of livestock to consume shrubs.

The East African pastoralist response documented here has been more immediate—a shift to goat and camel production—and there is field evidence that these simple adaptations have helped people of modest means to rapidly ameliorate the negative impacts of global climate and environmental change:

> … diversification of livestock species was associated with shorter periods of food deficit, better dietary intake and lower magnitude of household food insecurity……. Generally, livestock diversification significantly affects off-take and consequently improves access to food. Thus, multiple species herding does not only offer food products but also more ample choices for off-take, which can be liquidated in times of shortage and can smooth consumption (Megersa et al., 2013).

East African pastoralists have also been able to convince regional consumers to adjust their buying habits. Evidence of this flexibility is provided by the emergence of a new livestock commodity—commercially sold camel milk—first reported in 1990 (Herren, 1990) and now established in urban markets in Somalia, Ethiopia, and Kenya (Akweya et al., 2012; Anderson et al., 2012; Abdullahi et al., 2013; Noor et al., 2013; Elhadi et al., 2015; Gebremichael and Girmay, 2019).

In a recent keynote address to the Australian Rangeland Society, Walker (2019) noted the prevalence of mixed grazers and browsers on African savannas and the first glimmers of interest in Australia for domestic mixed-species goat husbandry. Huntsinger et al. note that American ranchers have "traded the

[4]Statistics Division, Food and Agriculture Organization of the United Nations Rome, Italy.

stability of mixed herds for the efficiency of uniform production, with most ranchers relying on cattle alone" (Huntsinger et al., 2010, p. 17). Eldridge et al. have questioned the distorting effects of "a single land use: pastoralism involving grass feeding livestock" (Eldridge et al., 2011, p. 720) and the coupling of degradation with bush encroachment in scientific assessments of ecosystem structure and functioning.

With little delay and minimal scientific support, East African pastoralists are already adjusting to a new woody world that ranchers in advanced economies and their scientific compatriots have now noticed but have taken few practical steps to accommodate.

FENCED ROTATION OR OPEN-RANGE MIGRATION

This section explores a possibility that would have been considered preposterous a decade or so ago: Migratory systems of production do a better job of distributing livestock over space and time than fenced, rotational systems of livestock and pasture management.

Multiple factors, including fundamental advances in theoretical and applied ecology, lend credence to this possibility, but declining scientific confidence in the utility of rotational grazing systems has also contributed. Between 1948 and 2003 roughly two out of every five articles in the *Journal of Range Management*—the preeminent journal of range science in North America—were about fenced "rotational" grazing systems (Brown and Kothmann, 2009). Reflecting this enthusiasm, for the last 50 years international development agencies have promoted fenced grazing schemes as a modern substitute for migratory livestock- keeping in pastoral Africa. These efforts met with limited success. Occasionally pastoralists did adopt fencing and deferred grazing, not necessarily because they thought it improved forage output or animal performance, but because it was subsidized or officially enforced, saved herding labor, established privileged (and sometimes private) access to collectively owned resources, or simply locked down their property rights. More commonly, donor-funded rotational grazing schemes collapsed whenever foreign personnel, money or enforcement were withdrawn (Sandford, 1981, 1983).

Interpreted at the time as irrational conservatism, pastoral reluctance to adopt rotational grazing makes sense in terms of the most systematic metanalysis yet conducted of the performance of these systems: "[S]ubjected to as rigorous a testing regime as any hypothesis in the rangeland profession," rotational grazing systems have been found to "convey few, if any, consistent benefits" and it is likely that "… a continuation of costly grazing experiments adhering to conventional research protocols will yield little additional information" (Briske et al., 2008, p. 11; see also Heady, 1961; O'Reagain and Turner, 1992; Holechek et al., 2001; Bailey and Brown, 2011; Hawkins, 2017). Despite the decades of negative or mixed results in the works cited above, the debate about the efficacy of rotational systems in semi-arid rangelands grinds on without resolution (Teague et al., 2013; Briske et al., 2014). The safest conclusion may be that the advantages of rotational systems are either modest and difficult to detect, or so contingent upon local circumstance or skilled management as to make them difficult to replicate. Irrespective of the ultimate outcome of the debate, at this late date rotational grazing seems unlikely to produce any dramatic breakthroughs[5].

Two recurrent features of migratory pastoralism set it off from the management practices associated with fenced grazing systems: the exploitation and potential amplification of environmental heterogeneity and the practice of herding/shepherding. These are discussed below, followed by an examination of the benefits and liabilities of fenced sedentary livestock systems vs. open-range migratory pastoralism.

Intrinsic Heterogeneity

Migration does not arise without functional environmental heterogeneity. If resources are constantly available, evenly distributed, or highly concentrated it makes little sense to engage in movement at the landscape scale—i.e., to migrate. A wide variety of environmental gradients encourage migration, including:

- Differences in elevation create vertical zonality in temperature, precipitation, vegetation, and the seasonal calendar, which all support transhumance—regular up-slope-down-slope movement to access resources and avoid extreme weather in mountainous areas (e.g., Barth, 1959).
- Across the temperate grasslands of the Eurasian steppes, changes in latitude create north-south horizontal zonality. As in mountainous areas, herds move both to access resources and avoid extremes of weather, but the movements might take place on a vast continental scale—north in spring tracking the green-up of the vegetation, south as winter approaches to avoid the worst of the snow and cold (Khazanov, 1994).
- Especially in the semi-arid tropics, precipitation gradients provoke movement. Lower rainfall areas provide high quality grazing in seasons when plants are growing, forage is relatively abundant, and herds need a nutritional boost to support reproduction. High rainfall areas provide abundant, low-quality forage in seasons when plants in lower rainfall areas are senescent, forage is scarce, and animals cannot afford to be selective. Migration occurs as herds shift from reproduction to survival by moving between areas of low and high plant biomass (Behnke et al., 2020).
- Topographically complex landscapes can support grazing habitats that are situated in close proximity to one another but differ markedly in their soils, drainage and vegetation characteristics. Because they are responding to micro-variations in their environments, herds may not migrate great distances (Scoones, 1995).

[5]The environmental impact of the fences themselves is also an issue. While noting that the ecological effects are complex and varied, a recent systematic literature review concluded that "Scientists have begun to consider the ecological merits of conservation fence removal … and we recommend the expansion of fence removal programs to other fence types. Over time, the restoration of large tracts of fenceless land will benefit ecosystems and the services they deliver" (McInturff et al., 2020, p. 982).

Despite obvious differences in scale, localized movements within a catena and long-distance migrations "are in reality exactly equivalent" (Bell, 1971, p. 92)—wildlife or livestock move along environmental gradients to access asynchronous pulses of resource abundance and escape temporary periods of localized scarcity. Following this strategy, heterogeneous environments can support larger migrant populations than similar but fragmented environments that are exploited by separate sedentary populations (Behnke and Scoones, 1993; Boone and Hobbs, 2004; Boone, 2005). Prior to the introduction of firearms and large-scale commercial fishing, the natural world provided evidence of the fecundity of the migratory strategy in the form of massive concentrations of animal biomass: the North American bison (*Bison bison*, Epp and Dyck, 2002) and passenger pigeons (*Ectopistes migratorius,* Schorger, 1955), the saiga antelope (*Saiga tatarica*) of the Asian steppes (Yagodin and Amirov, 2014), herds of migratory African herbivores (Venter et al., 2017), migratory fish stocks (Rosenberg et al., 2005)[6], and global whale populations (Roman and Palumbi, 2003).

The capacity of migration to also support large livestock populations has long been recognized (Behnke and Scoones, 1993) but frowned upon in conventional ecological theory as a cause of overgrazing and environmental degradation (Illius and O'Connor, 1999). Supported by recent advances in pastoral archaeology and ungulate ecology, this negative assessment is now subject to qualification.

Engineered Heterogeneity—Natural Lawns, Anthropogenic Glades, and Semi-Natural Landscapes

The impact of migratory livestock on rangeland resources is complex and defies simple characterization. In tropical environments characterized by extremely low and variable rainfall, droughts may be frequent enough to hold livestock populations in check and minimize the impact of their grazing on pastures (Ellis and Swift, 1988), a hypothesis confirmed by meta-analyses based on decades of field studies (von Wehrden et al., 2012; Engler and von Wehrden, 2018). Extending the non-equilibrium model of ecosystem dynamics beyond the semi-arid tropics, research now suggests that extreme cold may buffer vegetation from herbivore impacts in some temperate and arctic rangelands (Begzsuren et al., 2004; Kerven, 2004; Sternberg, 2012).

There nonetheless remain many pastoral environments in which livestock do affect their grazing resources. Some sense of current research on these more "equilibrial" grazing systems is revealed by examining a phenomenon of increasing analytical significance—nutrient hot-spots—concentrations of soil, vegetation, and herbivore fertility in the form of grazing lawns or glades scattered across rangeland landscapes.

[6]"Although there are about 30000 species of teleost fish [the taxonomic category containing 96% of all fish species], only a small fraction of them are currently known to be migratory. However, these few species are the dominant marine species in terms of biomass and numbers, and most of the world's fish catches are based on them" (Bauer et al., 2011, p. 74).

The concept of grazing lawns developed out of work on grazing successions on the Serengeti savannah in East Africa (Gwynne and Bell, 1968; Bell, 1971). Grazing successions referred to the regular sequence in which different ungulate species occupied an area. Generally, large-bodied bulk feeders moved in first, opening up the sward by removing coarser, more mature vegetation, and were followed by smaller-bodied more selective graziers who took advantage of the shorter, less mature, and more nutritious forage that had been exposed by the bulk feeders. Based on differences in anatomy, physiology, and dietary requirements, "The relationships between [herbivore] species in such a grazing succession can thus be seen to be facilitative rather than competitive," which explained in part both the large migratory populations of Serengeti ungulates and their propensity to form herds (Gwynne and Bell, 1968, p. 393).

In a series of seminal publications, McNaughton (1979, 1984) expanded Bell's concept of facilitation between grazing animals to include the facilitation of plant productivity by grazing, which created grazing lawns. The enhanced productivity of the lawns was achieved through compensatory plant regrowth in response to grazing and—over time—the development of grazing-tolerant grass species and plant communities with higher nutrient quality and productivity than vegetation in ungrazed areas (McNaughton op.cit.). Humans were not viewed as a dominant force in shaping these landscapes. The shifting mosaic of vegetation in the Serengeti was instead attributed, as McNaughton phrased it in the title of a 1983 paper, to "composite environmental factors and contingency" driving the distribution of large migratory herds (McNaughton, 1983, p. 291).

The effects of fertilization by nutrient recycling from dung and urine—the latrine effect—was initially characterized as "so well-known that it warrants little additional comment," at least from a biological perspective (McNaughton, 1979, p. 36), and through the 1990s investigations of the impact of soil fertilization on vegetation and herbivore behavior were indeed "relatively limited" (Augustine et al., 2003). Significantly, those studies that did exist tended to be conducted by researchers interested in the environmental impacts of pastoralists and pastoral livestock (Reid and Ellis, 1995; Young et al., 1995; Turner, 1998a,b).

After 2000 this literature expanded rapidly and focused on nutritional hotspots termed "grazing glades"—grass-dominated "islands of high fertility and high plant biomass" in wooded savannah environments (Muchiru et al., 2009, p. 322). Like grazing lawns, these grazing glades attracted high concentrations of both wild and domestic graziers (Young et al., 1995; Augustine et al., 2003; Muchiru et al., 2008; van der Waal et al., 2011; Porensky et al., 2013a). Unlike the lawns, however, the glades were situated on the dung left behind in abandoned livestock kraals and hence had a clear pastoral origin. The elevated levels of contemporary grazing, defecation and fertilization that researchers observed were perpetuating a legacy of past human occupation. The glades were also "creating a relatively permanent community that increases ecosystem heterogeneity" (Young et al., 1995, p. 97) through the redistribution of nutrients from peripheral bushland sites to the glades (Augustine et al., 2003) contributing to the heterogeneity (Muchiru et al., 2008; van der Waal et al., 2011; Porensky and Veblen, 2012) and biodiversity

(Donihue et al., 2013; Porensky et al., 2013a,b) of both wildlife and nutrient-poor savanna vegetation.

From the perspective of archaeology, Marshall et al. could declare by 2018 that "the processes creating these glades are well-understood" although "the full time-depth of their creation and effects on African savannahs are as yet unexplained" (Marshall et al., 2018, p. 387). A "virtual fluorescence of archaeological research in traditionally pastoral nomadic regions" (Honeychurch and Makarewicz, 2016, p. 342) has in the last two decades equipped archaeologists to answer these outstanding questions and the answers are unequivocal: "herders have had a role in structuring and diversifying African savannah ecosystems for up to three millennia" and:

> Pastoral Neolithic and Iron Age sites in diverse Kenyan savannahs demonstrate the spatial influences of niche construction by pastoralists on soil nutrients and savannah heterogeneity, on timescales that range from five centuries to three millennia (Marshall et al., 2018, p. 389).

The pastoral exploitation and amplification of environmental heterogeneity—and the capacity of archaeology to document these processes—is not confined to Africa. The Eurasian rangelands comprise the world's largest contiguous area of grazing (Babaev and Orlovsky, 1985; Mirzabaev et al., 2016), comprising 25% of the world's total rangelands and over 6% of the total world land area (FAOSTAT "permanent pastures"). The impact of pastoral livestock in pre-historic times across Eurasia is indicated by the spread of plant species with endozoochoric (ingested) seeds dispersed by herded animals, concentrations of plants with defenses against grazing, and—as in East Africa—grazing-mediated "hot spots" that contain nutritionally-rich vegetation (Spengler, 2014; Ventresca Miller et al., 2020). Six to eight millennia ago on the Tibetan plateau, pastoralists—in conjunction with Holocene climatic fluctuations and fire—transformed forests into alpine meadows suitable for herding (Miehe et al., 2009; Schlütz and Lehmkuhl, 2009). In southwestern Turkey within the last 600–700 years, pre-modern mobile pastoralists:

> [D]id not merely exploit agriculturally marginal land; they... transformed this territory into a productive herding landscape through the construction of infrastructure, altering vegetation patterns and water availability, and sheltering themselves and their animals with locally available materials (Hammer, 2014, p. 285).

In the Middle East as in East Africa, ancient pastoralists left a permanent mark on the land by creating what Hammer has called landscape anchors—"geographic foci that structured the spatial organization of local landscapes" (Hammer, 2014, p. 269).

Herding

The previous discussion documented the results of herd movement: Viewed in the medium term across seasons and years, herds track environmental variability; viewed in the long term across decades and centuries, they reinforce it. This section examines herding in the short term—moment by moment, day by day—to better understand how it achieves these outcomes. Putting aside a host of complicating factors, migratory livestock move like migratory wildlife to wherever they can find the most favorable conditions at any time. Unlike migratory wildlife, however, domesticated ungulates are accompanied by humans and animal priorities are subject to abridgement or refinement in light of human judgement and social, economic, and political considerations. Very briefly, the following case studies illustrate these human-livestock interactions.

The Nenets reindeer herders of the Russian Arctic (Dwyer and Istomin, 2008), and the Wodaabe Fulani cattle pastoralists of the African Sahel (Krätli, 2008; Krätli and Schareika, 2010) keep different livestock species in very different environments. Both groups are atypical in their unusually high level of herding skills, which bring into sharp focus a recurrent challenge facing livestock keepers on the open range—the need to reconcile human and livestock priorities and decision-making (Stammler, 2005; Istomin and Dwyer, 2010; Stépanoff, 2012). As the following discussion shows, half-wild Arctic reindeer (*Rangifer tarandus*) exemplify the capacity of the animals to influence the grazing agenda; conversely, the Fulani ability to refine the behavior of their exceptionally docile cattle illustrates the contribution of the herder.

Reindeer exhibit a radical degree of animal agency because they are only semi-domesticated. The most common long-distance migratory pattern for reindeer—both domestic and wild—is to follow plant growth "advancing north with the greening of spring pastures and retreating south as plants senesce in autumn ....between lichen-rich winter pastures in a forest zone and herbaceous summer pastures at windy locations on the coast, where insect harassment is reduced, or at high altitude" (Stammler in Behnke et al., 2011, p. 159). Because wild and domesticated reindeer are biologically similar and occupy the same grazing ranges at the same time, domesticated reindeer have the capacity to abandon their owners and join wild herds. This vulnerability makes controlling reindeer movement a paramount concern for Nenets pastoralists. Effective movement control has two elements—rounding up animals to keep the herd together and controlling the speed at which the assembled herd moves in a desired direction and away from dangerous terrain, predators, pests, and other herds (Dwyer and Istomin, 2008). The two processes—gathering the herd and moving it forward—are interdependent. Success in holding the herd together rests on knowing when the herd should move to new pastures, and the reindeer themselves play a central role in making this determination:

> [Reindeer are] very sensitive to even the slightest change to the environment. Thus, when making movement decisions, the herders, rather than constantly assessing an incalculable number of environmental factors and moving accordingly, generally attune their actions to environmental variability by responding to changes in reindeer behaviour alone.... [M]ovement is made according to (albeit not solely) the degree of effort that is required by the herders to keep his animals under control on this pasture. The herders move when reindeer no longer want to stay on the pasture (Dwyer and Istomin, 2008, p. 530).

"[R]eindeer pastoralism rests on successful deciphering of herd behavior by the herders" (Paine, 1994, p. 31), but domesticated reindeer must also accommodate human needs. Migratory routes are adjusted to reflect administrative boundaries or other institutional restrictions, to accommodate marketing or the resupply of herders, to permit herders to engage in non-pastoral activities such as hunting or fishing, or simply to give the humans a rest. Reindeer herding is a reciprocal relationship, a process of "day-to-day symbiotic domesticity" (Stammler in Behnke et al., 2011, p. 164).

In common with the Nenets and most other migratory pastoralists, the Wodaabe of West Africa follow a seasonal migratory cycle. They graze sand dunes early in the rains to exploit the ephemeral vegetation that emerges quickly following rain, moving as the dry season progresses onto clay plains with heavier soil that retains moisture and supports plant growth for a longer period. However, in the very low rainfall areas inhabited by the Wodaabe, seasonal regularity is complicated by the erratic spatial and temporal distribution of rainfall from year to year. By moving opportunistically in response to the unpredictable distribution of rainfall, the Wodaabe prolong the time their herds can graze on fresh vegetation before facing the hardships of the dry season:

> Wodaabe herders do not consider scattered rainfall as a constraint.... For them it is a naturally provided mechanism by which they can control the availability of fodder resources according to the stage of growth in which they have attained best nutritive value. If rainfall were equally distributed in time and space, grass would develop beyond the state of optimal nutritive value everywhere at the same time and herders could exploit it only for a rather short period. The scattered nature of rain brings about a sequential series of beginnings of the vegetative cycle within one pastoral zone that herders can systematically exploit.... (Schareika, 2001, p. 73).

This is not a risk-averse way to make a living. In their pursuit of the highest quality pastures on the margins of an unpredictable environment, the Wodaabe are—in a manner roughly analogous to a professional gambler—embracing the benefits that come from "living off" uncertainty (Krätli and Schareika, 2010).

The Wodaabe control their herds through breeding and socialization, to a level not possible among the Nenets with their half-wild animals. Over generations of cattle and humans, the Wodaabe structure their herds around matrilineal cattle lineages, know the genealogy of each animal, carefully regulate mating, and cull underperforming animals by selling them. The object of this breeding programme is to select animals capable of the high levels of mobility and selective feeding that will enable them to harvest the best forage in their environment. Anatomically, these are large animals capable of migrating long distances to reach the best pastures, and animals with a slender head and small muzzle, which enables them to eat the short, nutritious vegetation without ingesting soil. Social traits are also important. Bororo cattle are put at ease by the presence of humans and are loyal to their owners in particular, reducing their stress when they are handled:

> [H]uman-driven tasks are performed by these cattle in virtually complete absence of coercion. The cattle bred by the Wodaabe know nothing of enclosures, follow their herder of their own accord (rather than requiring to be herded from the rear) and it is common, in the bush, to see entire herds controlled by one or two young children waving only a twig (Krätli, 2008, p. 25).

This "persuasive management style" (Krätli, 2008, p. 26) permits the Wodaabe—who know their pastures intimately—to guide their cattle to "maximize opportunities for selective feeding" (Krätli and Schareika, 2010, p. 612).

> The Wodaabe are aware that cattle eat more (that is the herders' goal) when they like what they feed on. Therefore, the herders are always seeking to stimulate their animals' appetite by leading them to fodder that, in their experience, the herd will particularly appreciate (the herders talk about favoured fodder with reference to 'tastiness' and to how much the animals look 'at ease' when feeding on it). They prefer certain species for these characteristics and target them consistently. Moreover, they enhance feeding performance by avoiding half-dry grass during the rainy season, or pasture soiled or malodorous from cattle droppings (Krätli and Schareika, 2010, p. 611).

Managing for or Against Heterogeneity

There is considerable variety in the way both migratory pastoralism and fenced ranching are practiced, which makes it difficult to rigorously compare them. The preceding account nonetheless suggests that these two forms of extensive livestock production distribute livestock very differently across a rangeland environment.

Underlying these differences are contrasting responses to environmental heterogeneity. Migratory pastoralists respond to variability—both temporal and spatial—by moving to seize opportunities and avoid problems. By seeking to exploit environmental heterogeneity they can—in certain circumstances—amplify it, a pattern that is well-documented in the archaeological record and by the ecological research reviewed in this paper. The Nenets and Wodaabe case studies illustrate how these results are produced by migration. At the landscape scale, it is unlikely that different seasonal pastures will be exposed to uniform levels of grazing. Types of pasture that remain attractive for a long period of time but cover a small area may be exposed to more grazing pressure than extensive pastures that are useful for a short period. Landscape attributes that have little to do with forage—insect pests, predators, slope, aspect, water sources in semi-arid environments or protection from snow or cold in temperate environments—may also produce uneven levels of pasture use, as herds congregate or avoid areas for reasons other than forage availability. Any differences in grazing pressure will be compounded by seasonality. Operating in unpredictable environments, pastoral herds are unlikely to use exactly the same pasture patch from year to year, but they do tend to use the same kind of pasture every year and do so at the same point in the seasonal cycle of plant development. In such migratory systems different vegetation communities are repeatedly subject to stress at the same point in their growth cycle, and the level of stress is potentially high:

> "Migratory species, by avoiding seasons of resource scarcity or heightened mortality risk, may be able to sustain much larger populations than otherwise similar resident species. Indeed, migrants are often far more abundant than their closest resident relatives…and the community and ecosystems impacts are therefore bound to be of greater magnitude" (Holdo et al., 2011, p. 134).

Holdo et al. are referring in this quotation to wild migratory species, but their conclusions also apply to domesticated migrants. For semi-domesticated reindeer, the similarities between wild and pastoral herd movement are self-evident. The parallels are real but less obvious in the case of the intensively domesticated Wodaabe cattle. All the efforts of Wodaabe herders are directed at obtaining the best forage for their cattle. Subject to constraints like pest infestations, difficult terrain, or predator risk, freely distributing wild ungulates have the same objective. The art of Wodaabe herding is to facilitate a domestic analog for a natural process whereby herbivores pursue and attempt to match ephemeral resource distributions. When the opportunity arises, pastoral herds not only target the best pastures but exploit them selectively for the most attractive species within them, not necessarily "managing" but potentially affecting their forage base.

To the extent that they may unintentionally exacerbate resource heterogeneity, migratory systems are antithetical to the objectives of formal systems of grazing rotation. There is "little doubt that grazing systems result in better distribution of livestock and more uniform utilization of the range" (Stoddart et al., 1975, p. 297). Uniformity is promoted by a constant design feature of all fenced grazing schemes, whether they are based on rotation, deferred-rotation, rest-rotation, or short-duration. Unlike seasonal migrations, these schemes subject part of a ranch to stress or resting, and then reverse the process. No section is grazed or rested year after year in the same season. In this way, the intrinsic differences between paddocks within a grazing rotation are minimized by subjecting all of them to roughly equivalent levels of grazing pressure and compensatory relief, while rotating the periods of relief and stress annually or through the seasonal calendar: "Rotation of season of use on ranges unquestionably has advantages. Plants vary greatly in their season of palatability. Under rotation grazing, different plants will be grazed at one season then another resulting in all being more equally utilized" (Stoddart et al., 1975, p. 297). On degraded pastures, short-duration rotational systems have the added appeal of compelling livestock to graze a paddock unselectively, thereby consuming both preferred and less preferred vegetation and allowing preferred forage species to recover (Teague et al., 2008; Crawford et al., 2019).

In sum, animal decision-making is constrained in all rotational grazing systems, by fences at the paddock level and, in short-duration systems, by high stocking rates within paddocks. The assumption behind these systems is that humans need to take charge since they understand and can optimize forage-grazier interactions. The prolonged controversy over the efficacy of rotational grazing suggests, however, that this assumption may be premature. By contrast, in the absence of fences, herding in migratory systems is a consensual inter-species relationship in which humans have real but limited coercive powers. Since they are not sole decision-makers, humans do not need to perfectly understand the myriad interacting variables that drive these complex systems. They let—or are forced to let—their animals do some of the thinking for them, and different migratory patterns emerge out of the interplay between humans, livestock, and the changing environment. Rotational grazing systems are designed; migratory systems evolve.

In practical terms, with respect to livestock movement and distributions, the differences between migratory and rotational range management are considerable. If migratory grazing promotes heterogeneity, rotational systems suppresses it:

> "Prevailing rangeland management practices emphasizing even distribution of livestock use have decreased both temporal and spatial heterogeneity" (Derner et al., 2009, p. 111). Most management activities in domestic grazing systems promote uniform grazing distribution. At the landscape scale, herding, water development, and fencing are used to manipulate animal distribution, and may play a larger role in transforming native grazing systems than the substitution of domestic grazers for wild ones (Adler et al., 2001).

Two lines of research—both offering improved livestock production in combination with rangeland conservation—offer some indication of what it might mean to reverse the trend to uniformity by extending pastoral management practices into areas not currently occupied by traditional pastoral societies.

With respect to conservation, the management of grassland birds is instructive. Since 1966, bird species dependent upon grassland habitats have been the most rapidly declining category of birds in the United States (Fuhlendorf et al., 2012). While multiple factors are involved, these declines "were simultaneous with nationwide improvements in rangeland condition and rangeland health, as our profession has [conventionally] defined these terms" (Fuhlendorf et al., 2012, p. 583). Grassland bird species prefer rangeland vegetation of variable density, height, and species composition (**Figure 1**), and the bird species most in decline have been those dependent on either very tall or very short vegetation and bare ground, pastures in "poor condition" from the perspective of uniform pasture management.

> Traditional emphasis on homogeneous use of vegetation (i.e., "management to the middle") at the pasture scale has resulted in the lack of suitable habitat for grassland birds at the extremes of the vegetation structure gradient in semiarid rangelands (Derner et al., 2009, p. 116).

In tallgrass prairie, vegetation stands at different heights can be created by a combination of burning and the free movement of cattle or bison that are either attracted to or avoid patches at various stages of post-fire regeneration. By promoting spatial discontinuities in grazing pressure, a patchwork of burned, unburned, and recovering areas creates a shifting vegetation mosaic that does not significantly depress and can increase cattle weight gain (Fuhlendorf and Engle, 2004; Limb et al., 2011), stabilizes primary and secondary productivity over time (Allred et al., 2014; McGranahan et al., 2016) and increases wildlife

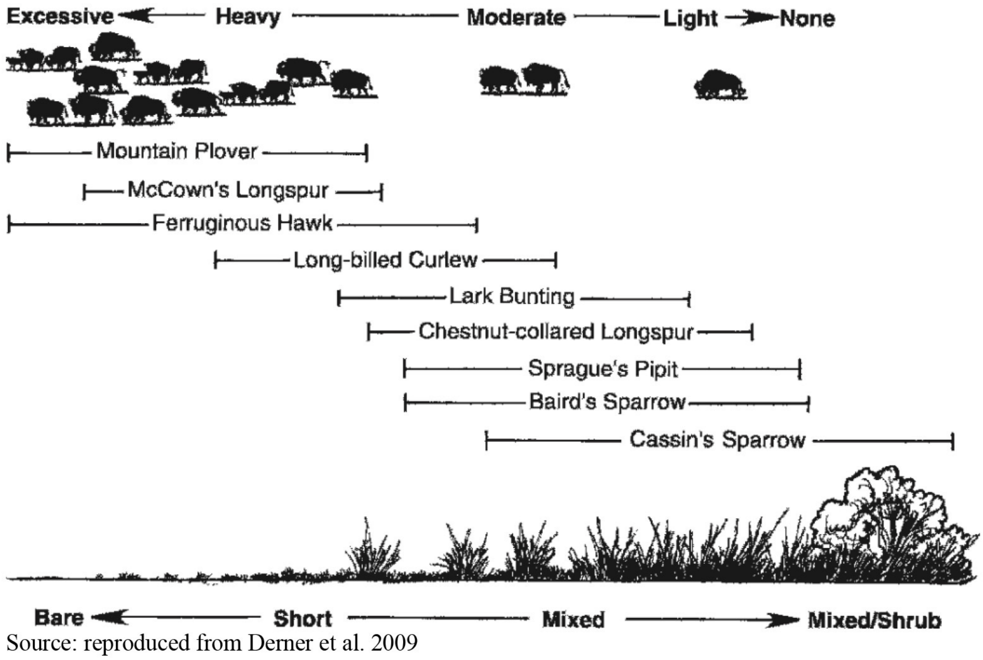

FIGURE 1 | Responses of grassland birds in shortgrass steppe to a vegetation structure gradient. Source: reproduced from Derner et al. (2009).

biodiversity (Fuhlendorf et al., 2006, 2010, 2017). As the variable buffalo numbers depicted at the top of **Figure 1** suggest, there is no proper rangeland stocking rate from the perspective of avian conservation, which requires a heterogeneous environment to meet the requirements of different bird species.

Consistent with a focus on conservation, work on "pyric herbivory" at spatial scales that enable migratory grazing has primarily taken place in conservation areas with herds of bison, not cattle, and not with herded cattle. In the published material on North America reviewed for this article, there was no indication that the advocates of pyric herbivory were aware of the similarities between it and migratory livestock husbandry[7].

For the proponents of pyric herbivory, the "uniformist" argument for rangeland use was exemplified by practices advocated in the standard textbooks of mainstream North American range management at the end of the last century (such as Stoddart et al., 1975; Holechek et al., 2001). For the proponents of an adaptive response to resource heterogeneity (Fynn, 2012; Fynn et al., 2016), the critique of uniform range use is directed at the "conceptual and theoretical flaws" underpinning a more recent manifestation of homogenous rangeland exploitation—short duration rotational grazing schemes (Fynn, 2012, p. 324). It is argued that the rigidity of these systems imposes artificial constraints that interfere with the free circulation of grazers in a typically pastoral migratory pattern, between "high-quality resources, to enable population growth, and reserve or buffer resources, to sustain the population after favored resources have been depleted, or are no longer accessible" (Owen-Smith and Novellie, 1982, p. 768). With minimal awareness of their similarity to pastoral migratory practices, recommendations for improved management are modeled on wild herbivore research and aim to create "similar heterogeneity in commercial rangelands … as well as … smaller conservation areas" (Grant et al., 2019, p. 7). With more ambition, others see the exploitation and enhancement of functional environmental heterogeneity as a basis for the management of broad landscapes and for wildlife-livestock co-existence on African savannahs (Fynn et al., 2016, 2019).

There are, in sum, multiple technical reasons to be optimistic about the future of migratory pastoralism and about the possibility that it can and should contribute to the improved design of all kinds of extensive livestock production. As reviewed in this paper, this optimism is grounded in progress in at least two distinct areas of scientific research:

- Advances in pastoral archaeology have recalibrated our understanding of the pristine, transforming apparently "natural" rangelands into "working wilderness" (Sayre, 2005) that has been shaped on an evolutionary timescale by both domesticated and wild herbivores.

[7]The similarity between pastoral and wildlife migration is noted in a paper advocating pyric herbivory for the restoration of abandoned cropland in Kazakhstan (Brinkert et al., 2016) and by Fynn et al. (2019) in a consideration of the role of mobility in the exploitation of functional environmental heterogeneity by both wild and domesticated ungulates.

- With respect to rangeland science, pyric herbivory emphasizes the use of engineered disturbance to enhance heterogeneity and build resilience, while the strategic management of functional heterogeneity recognizes mobility as an effective and sustainable use of rangeland resources. These approaches challenge both the uniformity-enhancing practices of mainstream range management in the last century and the restrictive practices of rotational grazing schemes. These approaches also constitute a significant rapprochement between migratory pastoralism and rangeland science and provide an unintentional legitimation of existing migratory practices.

RANGELAND TENURE—PRESERVING SCALE

As Huntsinger observed, 'The name, "rangeland" implies a land for ranging' but "The extent and inherent flexibility of pastoral systems clashes with the increasingly fragmented landscapes and hardening borders of today's world" (Huntsinger, 2016, p. 316). Without large areas of open rangeland, migratory livestock production is a practical impossibility. This section draws on the example of indigenous pastoral land tenure systems in Africa to identify modern property arrangements that could meet the needs of today's migratory ranchers.

The commodification of rangelands in the Americas, Australia, and southern Africa occurred several centuries ago with European colonization and the spread of the "Euro-American ranching complex" (Strickon, 1965). Well into the middle of the twentieth century, however, much of the rangelands of pastoral Africa and Asia had escaped commodification. State socialism and pastoralist collectivization held the line in Soviet Central Asia (Kerven et al., 2020) and Mongolia (Sneath, 2003), as did the Chinese Communist Party in China's western provinces (Banks, 2003). In sub-Saharan Africa, the limited administrative reach of newly-created nation states left marginal pastoral areas to their own devices, and many if not most African pastoralists gained access to natural resources by being members of indigenous political communities rather than citizens of nation states (Cunnison, 1966; Dyson-Hudson, 1966; Hoben, 1988; Bassett, 1993; Turton, 1994).

Indigenous land tenure regimes provided the institutional framework that sustained Africa's open rangelands and associated migratory systems of livestock production, but they have not been robust in the face of market penetration and the expanding power of national administrations. In recent decades, the pastoral conception of land rights as an entitlement defined by group affiliation has been effectively challenged by a commercial concept of rangeland as a privately-owned and tradeable commodity secured by legal title backed by the power of the state (Behnke, 2018). These legal changes have been accompanied by rangeland fragmentation, reduced pastoral mobility, and increased environmental degradation. It is unclear to what extent these changes have been brought about by the erosion of indigenous land tenure systems or by other developments that have occurred simultaneously—increased population pressure, the growth of small towns in pastoral areas, land conversion for agriculture, mining and industry, the attractions of urban services and wage employment, and the expansion of protected conservation areas (Liao et al., 2020; Lind et al., 2020).

Just as the rangeland sciences are on the cusp of understanding the value of livestock production conducted at a landscape scale, it would appear that many African pastoralists are losing their capacity to do so. Contemporary Africa, therefore, provides few obvious lessons for the design of successful pastoral tenure systems, but the ethnographic record does contain numerous examples of indigenous tenure systems that, until recently, did operate at landscape scales. If these historical systems are being rendered obsolete, the "design principles" that they exemplify may nonetheless indicate the functional characteristics required of any successful modern replacement.

At least three recurrent features of traditional African pastoral tenures have a functional significance—their communal ideology, the collective benefits they confer, and their exploitation of the partible nature of property rights. This section argues that recent innovations in pastoral tenure in ranching areas of southwestern USA are pioneering approaches to rangeland tenure that duplicate in a legalistic and heavily bureaucratized institutional setting these functional attributes of historical African tenure systems.

Commodification and Conservation

In *The Great Transformation* Karl Polanyi famously declared that land and labor were fictitious commodities (Polanyi, 1944). By this he meant that land and labor were not items produced for the purpose of buying and selling. Labor was a monetarized version of our fellow human beings, land was commodified nature, and both humans and nature existed independent of market relations.

The significance of Polanyi's argument for an understanding of global capitalism may be debated, but its relevance to rangelands is unequivocal. In the community-secured property systems that once dominated pastoral Africa, group viability was paramount because it was the quasi-sovereign community that collectively defended a territory. Group membership through descent and shared political purpose, not purchase or written title, granted access to landed resources conceived of as a shared and inalienable patrimony (Behnke, 2018). State incorporation and market penetration have effectively challenged this concept of the value of land. Even without legal recognition, vernacular, land markets now flourish (Chimhowu and Woodhouse, 2006), and enclosure is increasingly an African "default mode of development" (Woodhouse, 2003). The commodification of rangeland is particularly problematic for pastoralists. With market penetration, rangelands that are naturally heterogeneous become commercially heterogeneous. As areas or resources acquire monetary value, it becomes profitable to excise the valuable bits that warrant "development," leaving behind a fragmented, shrunken, residual rangeland environment for those productive activities such as pastoralism that are less susceptible to investment and intensification. Frequently, neither land use zoning nor the reservation of land by treaty have halted this process (Huntsinger and Hopkinson, 1996; Plieninger et al., 2012; Tyler et al., 2020).

In the modern world, at least one ideologically motivated form of land holding—the setting aside of protected areas for nature conservation—has the public recognition and political status to reliably enforce the old pastoral vision of land as a shared, intergenerational patrimony. If history provides any indication of the future, large-scale migratory pastoralism must make peace with nature conservation if it is to prosper[8].

Collective Benefit

A communal ethic may have sustained indigenous pastoral tenure regimes, but it does not explain their emergence. Also relevant are mundane considerations of gain and loss that can be conveniently summarized under the heading of "collective benefit."

The concept of collective benefit is exemplified by work conducted by Wade (1987) on community-level institutions in a semi-arid region of South India. Some of the villages in Wade's study area were "corporate" in that the villagers had created public institutions to collectively manage two of the productive resources upon which their livelihoods depended—irrigation water and livestock. Other villages in the same region made no such effort. Wade attributed these contrasting institutional outcomes to different incentive levels for joint action. In irrigated areas, corporate villages were located toward the tail-end of canal systems where water was scarce and farmers were strongly motivated to regulate its use, which was only possible if they acted together. At the head of canal systems where water was plentiful, individual farmers could act on their own to meet their water needs and collective institutions did not emerge. In rainfed farming areas, corporate villages were situated on rich, water-retentive soils that attracted large numbers of outside livestock that threatened the welfare of village farmers. In these villages, the control of stock numbers depended on a coordinated response, which local farmers undertook. Villages with poor soils attracted fewer livestock and took no such action. Wade concluded that the villagers in his study area were "likely to follow joint rules and arrangements only to achieve intensely felt needs that could not be met by individual action." Collective action was contingent on what Wade called "collective benefits," benefits that individuals acting alone could not obtain: "The opportunities for avoiding losses or boosting income by collective action will be taken only if the losses or gains are large" (Wade, 1987, p. 230).

Migratory African pastoralists have long engaged in collective action to secure important benefits that were unattainable for the isolated individual. Only group solidarity could provide individual security of tenure in unadministered, competitive, and potentially violent political environments and only collective territories were large enough to provide access to dispersed resources in variable natural environments. These collective benefits are now being undermined, politically by state incorporation and technologically by inputs that reduce the need for herd mobility, such as feed supplementation and the artificial provision of stock water. If collective action is to re-emerge, new sources of collective benefit are required (Behnke, 2008, 2018).

Partible Rights

That property is a bundle of rights and that different parties can own different parts of the bundle is not unusual. One party may own surface rights but not mineral rights, rights of possession but not disposal (as in legal trusts), temporary occupancy rights (as in time-sharing arrangements), or rights of access and transit over land that they do not otherwise control (Van de Laar, 1990):

> More than one party can claim sole ownership interest in the same resource. One party may own the right to till the land, while another, perhaps the state, may own an easement to traverse or otherwise use the land for specific purposes. It is not *the* resource itself which is owed; it is a bundle, or a portion, of rights to *use* a resource that is owned (Alchian and Demsetz, 1973).

In migratory systems, mobile producers with a temporary interest in using an area routinely confront permanent occupants and other mobile producers. The land tenure systems that legitimate these encounters must represent the interests of both primary and peripheral rights holders with a multitude of different agendas but with important intersecting collective interests. For African pastoralists, the partibility of use rights has been an important mechanism for adjudicating the needs of these diverse categories of users. Different groups or individuals are entitled to use different resources in the same area, or to share in the use of a resource by using it for a limited period of time, by exploiting some aspects of its productivity but not others, or by using it only under certain circumstances. Migratory herders might, for example, have grazing rights in areas where they had limited rights to stock water; or be entitled to graze natural pastures with (or without) additional rights to graze the harvest residues on local farms, engage (or not) in cultivation themselves, or develop new water points, etc. Because of their diverse origins and interests, the participants in these systems of coordinated resource use frequently do not constitute homogeneous, readily identifiable corporate groups or occupy a clearly demarcated territory (Behnke, 1994; Turner, 1999; Fernandez-Gimenez, 2002).

For this, and a variety of other reasons, in pastoral Africa, indigenous systems of collective resource use deviated in fundamental ways from the classical model of the successful common property system (Wade, 1987; Ostrom, 1990). This conclusion has policy implications for efforts to encourage cooperative systems of pastoral resource use. In Africa, these efforts have often attempted—with mixed success—to foster the creation of socially and geographically bounded common property regimes. Indigenous pastoral systems never conformed to this model and their distinctive organization suggests that

[8]As long as commercial development can be held at bay, state ownership is another non-capitalistic, non-commodified form of land ownership. However, given the growing public awareness of environmental issues, continued pastoral access to public land may also rest on successfully addressing the concerns of conservationists, as discussed later in this paper with respect to state-owned land in the western United States.

securing flexible access to extensive rangelands requires an alternative approach.

Conservation Easements and Grass Banks

Half a century ago international development agencies mistakenly promoted American ranching as a template for the reform of "backward" African and Asian pastoralism (Sandford, 1983; Behnke and Kerven, 1994). Decades later, some American ranchers might finally fulfill their potential as a positive role model. Faced with bureaucratic and legalistic restrictions of the kind that have overwhelmed many pastoral communities, these ranchers are developing cooperative forms of rangeland tenure with the potential to maintain some of the functional attributes of the open-range. To do this they have adopted new legal instruments that replicate the functionality of indigenous African tenures—an emphasis on collective benefit, exploitation of the partibility of property rights, and the recognition of wider social and conservation interests that restrict the free play of market forces.

With respect to collective benefit, some contemporary American ranchers have organized themselves to appropriate or defend a wide variety of "intensely felt needs that could not be met by individual action" (Wade, 1987, p. 230).

- In Texas, where most ranches are on private land, an increasingly profitable source of additional ranch income is commercial hunting. Game animals move around, however, showing little respect for property lines. This means that landowners who have invested in raising game animals cannot depend on harvesting them or selling the rights to harvest them, which encourages underinvestment in protecting wildlife and over-harvesting. In response, Texas ranchers and state officials have brought landowners together to form wildlife management associations that promote and regulate the hunting of a common pool resource—an itinerant game population (Huntsinger et al., 2014).
- From about 1900 until the 1980s the US Forest Service suppressed fires on the land it managed and "the regular fires that graziers used to keep land open for grazing were criminalized and halted" (Huntsinger et al., 2010, p. 23). When they were finally adopted, policies to encourage controlled burning did not bring relief. The intermingling of public and private lands and the involvement of multiple federal and state agencies each with its own procedures made coordinated action difficult; often little burning actually took place. Since conflicting regulations and bureaucratic inertia were the problem, more regulations and more bureaucracy were unlikely to be the solution. Coalitions that brought together government agencies, environmental groups, ranchers, and scientists have been more successful (Sayre, 2005).
- In the western USA, there are more than 5,000 migratory ranchers who move seasonally, usually between lowlands that they lease or own privately and higher altitude summer ranges that are publicly owned and managed by federal government agencies. Permits to graze public land are economically valuable, providing about 47% of income on ranches that rely principally on livestock production for their income (Huntsinger et al., 2010). These tenure rights have proved to be insecure because management agencies have imposed new restrictions on grazing and animal numbers. As a result, between 1980 and 2005, the amount of forage consumed on US Forest Service land declined by nearly 40 percent and the number of pastoralists declined by nearly 64 percent (Huntsinger et al., 2010). Restrictions to grazing rights on public land are an important reason why ranchers go out of business.
- Loss of rangeland to suburban sprawl, "ranchettes" and second homes is especially acute around metropolitan areas or touristic sites but is a threat to almost all ranching areas in the American West. The resulting parcelization complicates environmental management and is associated with habitat degradation and loss of biodiversity and ecosystem services (Havstad et al., 2009; Gutwein and Goldstein, 2013). Deteriorating conditions on the peri-urban edge and the increasing discrepancy between the income available from a ranch vs. the ranch's sale value for development also promote what has been characterized as an "impermanence syndrome" when ranchers conclude that selling for non-agricultural development is inevitable and stop investing in their operations (Berry and Plaut, 1978, cited in Liffmann et al., 2000, p. 363). These individual decisions often have wider social impacts:

> "A single ranch-owner's decision may spell the fate of many thousands of acres. Landowner decisions affect more than their own property, as nearby properties are also influenced through the fragmentation of land use, weakening of the agricultural infrastructure, changing land values, and the creation of new growth nodes in previously undeveloped areas" (Johnson, 1998, cited in Liffmann et al., 2000 p. 363).

Because of the scale of ranch properties and the tightly integrated character of ranching communities, the loss of individual ranchers is not just an individual problem, but a collective one as well, which suggests that any solution may also need to be collective.

Of the collective challenges enumerated above, it is the last two—insecurity of tenure on public land and loss of private rangeland to alternative uses—that constitute the most geographically widespread threats to ranching in the American West. These two threats have also elicited what is arguably the most creative response. Part of this response has been an organized effort to dispel the hostility between conservationists and ranchers by making conservationists aware of the environmental benefits of grazing and, conversely, by convincing ranchers that conservation does not necessarily entail more regulations that interfere with their ability to run a business[9]. Also important has been a new legal device—the conservation easement—that has grown exponentially in popularity in the United States since the 1980s (Kay, 2016).

Conservation easements are voluntary legal agreements that recognize private ownership but limit the way private land can be used. Easements—like traditional pastoral tenure systems—rest on the notion that property is a bundle of rights that are divisible. In the case of conservation easements, property owners are typically paid by a government agency or non-profit land trust to relinquish the right to sell their land for subdivision or non-agricultural development. Private owners are then compensated for the reduced commercial value of their land while retaining the right to privately own, manage, sell or bequeath it (Liffmann et al., 2000). Conservation easements are attractive to ranchers who want to continue ranching but also want to realize some of the commercial development value of their ranch. The arrangement is attractive to conservation interests because easements are permanent, cheaper to acquire than outright land purchase, and are managed by their owners rather than hired employees (Brunson and Huntsinger, 2008).

Land owners who agree to conservation easements are rewarded financially through savings on their taxes and by payments that compensate for the opportunity cost of forgone development rights. In at least one case, the Malpai Borderlands Group, US ranchers have also traded their easements not for money but for grazing rights on the land of the non-profit organization that holds their easement (Sayre, 2005). The amount of grazing acquired through these "grass banking" agreements is based on the cost of leasing grazing land equivalent in value to the monetary compensation it has replaced. The Malpai easement contracts also contain clauses that void an easement agreement if ranchers lose access to state and federal grazing land through no fault of their own, something that ranchers insisted upon because the viability of their livestock operations depended on such access. Perhaps unexpectedly, the altered but conditional conservation status of private land has also had a beneficial impact on securing access to government land:

> Malpai's easements have strengthened relations between ranchers and agencies, because the agencies recognize the benefit of preventing development of private lands to the conservation of adjacent public lands. In effect, the clause holds both the ranchers and the agencies to a higher standard of cooperation and effective management, as the former seek to maintain their leases and the latter seek to prevent the clause from being exercised (Huntsinger et al., 2014, citing Sayre, 2005; Rissman and Sayre, 2012).

[9]Research documents the environmental benefits of ranching relative to alternative forms of land use in the American West. Maestas et al. (2003) examined the comparative levels of biodiversity on exurban developments, ranches, and nature reserves in a Colorado watershed. They concluded that "Reserves are often assumed to protect biodiversity, but our results suggest that reserves were somewhat ecologically degraded. Ranches can be more effective than reserves at maintaining native biotic communities in some instances, suggesting that the conversion of ranchland to exurban development has negative consequences" and that "efforts to protect the natural heritage of the Rocky Mountain West may require less reliance on nature reserves and greater focus on private lands" (Maestas et al., 2003, p. 1432–1433).

In sum, conservationists and ranchers in the American West have pioneered the development for rangelands of a newly popular legal instrument—the conservation easement. These easements monetarize conservation values and recognize individual property rights and, hence, are compatible with market-based capitalism. But they also restrict the ability of individuals to alienate property in which a wider community has a permanent interest.

An additional feature of the Malpai programme—grass banking—provided an institutional framework for sharing privately owned rangeland. Grass banking involves the bartering of forage for conservation benefits. In Malpai these exchanges involved the trading of grazing privileges for conservation easements, but a wide range of other conservation activities can also be exchanged for forage, including the protection of endangered species, burning to reduce bush encroachment or control invasive plants, or grazing exclusion to rehabilitate degraded pastures. Enthusiasm for grass banking was based on a perceived win-win situation:

> In theory, conservationists "win" because treatments, such as prescribed fire, that should improve overall health of an ecosystem, are implemented. Ranchers "win" because the grassbank provides forage to them, often at a discounted rate, so they don't suffer any economic harm as a result of the treatments which can require them to vacate their regular grazing pastures. Finally, local communities whom value "working landscapes" "win" because it is assumed that ranchers can remain in business while restoration treatments occur, thereby helping sustain the local economy and reduce the risk of subdivision (Gripne, 2005, p. 6).

By the early 2000s in the western US, more than twenty grass banking projects existed and more were being planned, but it is unclear how many new projects have been started since that time or how many of the original projects have survived up to the present. US tax laws required grass banks run by non-profit organizations to operate on a *quid pro quo basis* "where the economic value of the conservation benefit equals or exceeds the value of the forage' that was traded in return" (Gripne, 2005, p. 134). Many smaller grass banks did not have sufficient funding, personnel, or scale to meet this demand and hence were not economically sustainable, and a pilot effort by ranchers to form a collective grass bank to trade grazing rights among themselves failed to attract sufficient funding and collapsed (Gripne, 2005). Underlying these difficulties may have been a difference of opinion between conservationists and ranchers as to the purpose of grass banks. Conservations viewed grass banks as an innovative conservation tool; there are suggestions that ranchers saw them as a practical arrangement for managing drought and forage shortfalls on their home properties.

From an international perspective, the limited success of grass banking in the US may be less significant than its legalized status and formal organization. In both Australia and among newly privatized freeholders in Kenya, pastoralists have invented informal workarounds that allow them to share the grazing on their private holdings (McAllister et al., 2006; Mwangi, 2007; Lesorogol, 2010). Adjusted to meet local conditions, grass banking may provide a mechanism for strengthening these arrangements by legally recognizing shared grazing rights on private rangeland. Taken in combination, grass banks and conservation easements address what Fernandez-Gimenez (2002) has called the "paradox of pastoral tenure"—the simultaneous need for tenure security and for flexible access to extensive, erratically productive rangeland resources.

This essay began with the assertion that pre-industrial pastoralism had something to teach commercial ranchers. We close with the observation that there is a significant convergence between some of the features of traditional pastoral tenure systems, conservation easements, and grass banks. There is also evidence that commodification and individualization of property rights are taking place spontaneously in what were formerly open range areas in the developing world (Behnke, 2008; Bassett, 2009; Schareika et al., 2020), and that we may need to look for ways to accommodate this reality. It is, therefore, encouraging that some African conservationists are interested in developing "mobility-based livestock and wildlife management strategies" that exploit environmental heterogeneity and are based on institutional invocations that bear a strong resemblance to grass banks and conservation easements (Fynn et al., 2016, p. 390)[10]. American ranchers may at last have some development ideas that genuinely meet the needs of their Asian and African counterparts.

[10]"[T]o enhance functional heterogeneity within PAs [protected areas] and to forestall the confinement of wildlife to 'less functional isolated protected patches' with the growth of human populations, Fynn et al. advocate that": [C]ommunities could be given grazing concessions within non-sensitive parts of PAs. Communities could benefit from grazing concessions within PAs by greater adaptive foraging options for livestock across larger landscapes (as do the wild herbivores), access to forage reserves during the dry season and greater ability to move livestock away from crop fields during the cropping season (Fynn et al., 2016, p. 390, 393).

CONCLUSION

The organizers of this collection of papers asked the contributors to reimagine or redesign "monotonic pastoralism," which they characterized as "pastoralism with the single objective of maximizing animal production and/or profit [that] has transformed landscapes, diminishing biodiversity, reducing water and air quality, accelerating loss of soil and plant biomass, and displacing indigenous animals and people" (Gregorini, 2019). This essay examined three central components of extensive livestock production—herd composition, grazing/pasture management, and rangeland tenure. In all of these areas, neither fenced nor open-range forms of extensive pastoralism are so dysfunctional as to constitute monotonic pastoralism, but they do face a number of shared problems. Set aside the presumption that either one of these systems of extensive production is technically or institutionally more advanced than the other, and it turns out that each has lessons for the other. Is it so farfetched to look back (with renewed respect) to the future?

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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Livestock in Evolving Foodscapes and Thoughtscapes

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Humanity's main societal and epistemic transitions also mirror changes in its approach to the food system. This particularly holds true for human–animal interactions and the consumption of animal source foods (red meat especially, and to a lesser degree dairy, eggs, poultry, and fish). Hunter-gathering has been by far the longest prevailing form of human sustenance, followed by a diffuse transition to crop agriculture and animal husbandry. This transition eventually stabilized as a state-controlled model based on the domestication of plants, animals, and humans. A shift to a post-domestic paradigm was initiated during the 19th century in the urbanizing populations of the Anglosphere, which was characterized by the rise of agri-food corporations, an increased meat supply, and a disconnect of most of its population from the food chain. While this has improved undernutrition, various global threats have been emerging in parallel. The latter include, among others, a public health crisis, climate change, pandemics, and societal class anxieties. This state of affairs is an unstable one, setting the conditions of possibility for a new episteme that may evolve beyond mere adjustments within the business-as-usual model. At least two disruptive scenarios have been described in current food discourses, both by scientists and mass media. Brought to its extreme, the first scenario relates to the radical abolishment of livestock, rewilding, a 'plants-only' diet, and vegan ideology. A second option consists of a holistic approach to animal husbandry, involving more harmonic and richer types of human–animal–land interactions. We argue that – instead of reactive pleas for *less* or *none* – future thoughtscapes should emphasize '*more* of the *better.*'

Keywords: livestock, human–animal interactions, veganism, vegetarianism, meat, dairy, health, sustainability

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INTRODUCTION

Animals – and the foods derived therefrom – take up a prominent place in human thoughtscapes. They have been granted important semiotic and epistemic status, as in Lévi-Strauss (1963) dictum that animal species are not all that much 'good to eat' but rather 'good to think (with).' Their position, however, should not be understood as a fixed one but rather as an evolving constellation of meaning (Murcott, 2003; see, for instance, Safina, 2016). In *The Road to Wigan Pier*, Orwell (1937) suggested that 'changes of diet are more important than changes of dynasty or even of religion.' Be that as it may, novel views on food have indeed paralleled moments of deep social transformation. Because animal source foods have always held a key position in human diets, whether eaten in abundant quantities or not, such shifts involve altered human–animal relationships (Leroy and Praet, 2017).

Hominins and other animals have co-evolved intimately. Modern humans (*Homo sapiens*) have spent some 300,000 years as small, mobile bands of hunter-gatherers, situating animals firmly within their localized cosmologies. The eating of animal source foods is therefore tightly coupled to human biosocial evolution (Stanford and Bunn, 2001). After a transition period from foraging to more settled communities, new societal models emerged during the Neolithic era and eventually organized themselves around the concept of domestication (Scott, 2017). Animals, now as livestock, became increasingly more *useful*. As such, they transitioned from a co-evolutionary component of an ecological trophic cascade into a resource that could be handled, controlled, and utilized. During the 19th century, a post-domestic model of human–animal interactions was adopted in the West, in particular within the urban populations of the Anglosphere (Bulliet, 2005). This shift is typified by a far-reaching industrialization of the food chain and public alienation from the everyday realities of animal husbandry. In contrast, animal husbandry worldwide is still mostly situated within rural communities and typified by frequent and intimate human–animal interactions.

This post-domestic model that has since overtaken urban foodscapes is now becoming unstable, as doubts and anxieties about the impact of livestock production on the environment and on human and animal health and wellbeing are accumulating. Although a business-as-usual scenario cannot be entirely excluded, disruption is likely to occur in the mid or long term. This has the potential to redefine the meaning of animal husbandry drastically. Livestock may become either obsolete – which will steer humanity into a novel dietary paradigm – or start playing a role at the forefront of healthy and sustainable foodscapes, thoughtscapes, landscapes, and ultimately socialscapes. All four will be relevant to serve as a foundation for new societal templates, matching humanity's individual and collective needs for the provision of adequate nutrition, societal concord, and purpose.

THE EVOLVING ROLE OF ANIMALS IN HUMAN FOODSCAPES AND THOUGHTSCAPES

Mechanisms of Change

A theoretical model to describe the epistemic transitioning of human–animal interactions has been proposed previously by Leroy (2019). In brief, a historically contingent assemblage of interconnected biosocial needs is assumed (further defined as *strata*), loosely based on Maslow's (1943) theory of human motivation (**Figure 1**). It outlines a deep-seated human dependence on animals and the foods, services, and meaning they provide, including the basic physiological need for nutritional security, the social desire for communal bonding, and the individual urge for status and eudaimonic pursuit. For a detailed discussion of the various needs that are contained in this model, we refer the reader to a previous study by Leroy and Praet (2015).

Figure 1 represents the flux of these needs from the pre-domestic episteme into the domestic and post-domestic ones (cf. Bulliet, 2005). They should be viewed as *emerging* responses to (ecological or infrastructural) change and not as a linear, teleological progression of predictable events. Emergence affects all of a system's elements and causes a 'perpetual transition of nature into novelty' (Whitehead, 1920), until change becomes disruptive and a novel epistemic model emerges. This conceptualization is useful as a heuristic, but should not be seen too restrictively, as hybrid situations can be found within the larger historic mosaic of global sustenance solutions (Scott, 2017). Yet, each model represents a self-organizing structure of meaning and should be approached as such. As meta-stable 'solutions' to historical 'problems,' needs are formed through the constitutive actions of *stratification* and provisionally stabilized by *coding* (in the jargon of Deleuze and Gauttari, 1987).

Over millennia, animals (and the foods derived therefrom) have accumulated a lot of biological, social, and semiotic capital, which is used to stabilize the various strata, at least in a temporary manner. As such, the lower strata reflect a biological desire for nutrition, largely governed by the materialities of genetics and biochemistry (cf. Christakis, 2019), whereas the more supple social needs of the upper strata are stabilized by language and culture predominantly.

The Pre-domestic Era: The Kill as Focal Point of Hunter-Gatherer Communities

The pre-domestic model (cf. **Figure 1**) refers to the needs of hunter-gatherers for animals as essential providers of nutrients, clothing, tools, as well as social cohesion. They have emerged from what Deleuze and Gauttari (1987) named 'machinic' assemblages of *bodies* (carcasses, marrow, nutrients, hands, brains, skin, bone, animals, spears, fire, stone, ochre, etc.) and collective assemblages of *enunciation* (e.g., in dance, song, rite, myth, or painting). For a discussion on how the appearance of scavenging, hunting, and meat eating are to be considered as 'solutions' to (ecological) 'problems' within the hominin record, we refer to Stanford and Bunn (2001) and Andrews and Johnson (2019).

To obtain a functional human community capable of generating (food) security, stabilization of the individual needs of its members into a collective one was achieved by smoothening intraspecific aggression. According to Burkert et al. (1987), the latter was redirected from the clan onto the prey in the interest of the objective of the hunt. The kill serves as a focal point around which social behavior is coordinated, a process that involves ritualistic and transactional activities. Although the prey remains fundamentally 'food to be taken,' the killing is a *dark event* to the human psyche, evoking horror and guilt layered with significance (Leroy and Praet, 2017). Ritual serves as the creative channeling of anxiety – to give back what was taken – whilst anthropomorphization blurs the borders between the animal and human, between prey and predator. Animals act as insiders *and* outsiders to human communities, a status that also typifies that of the shaman. The need for communal bonding, with all its cultural and spiritual connotations, not only

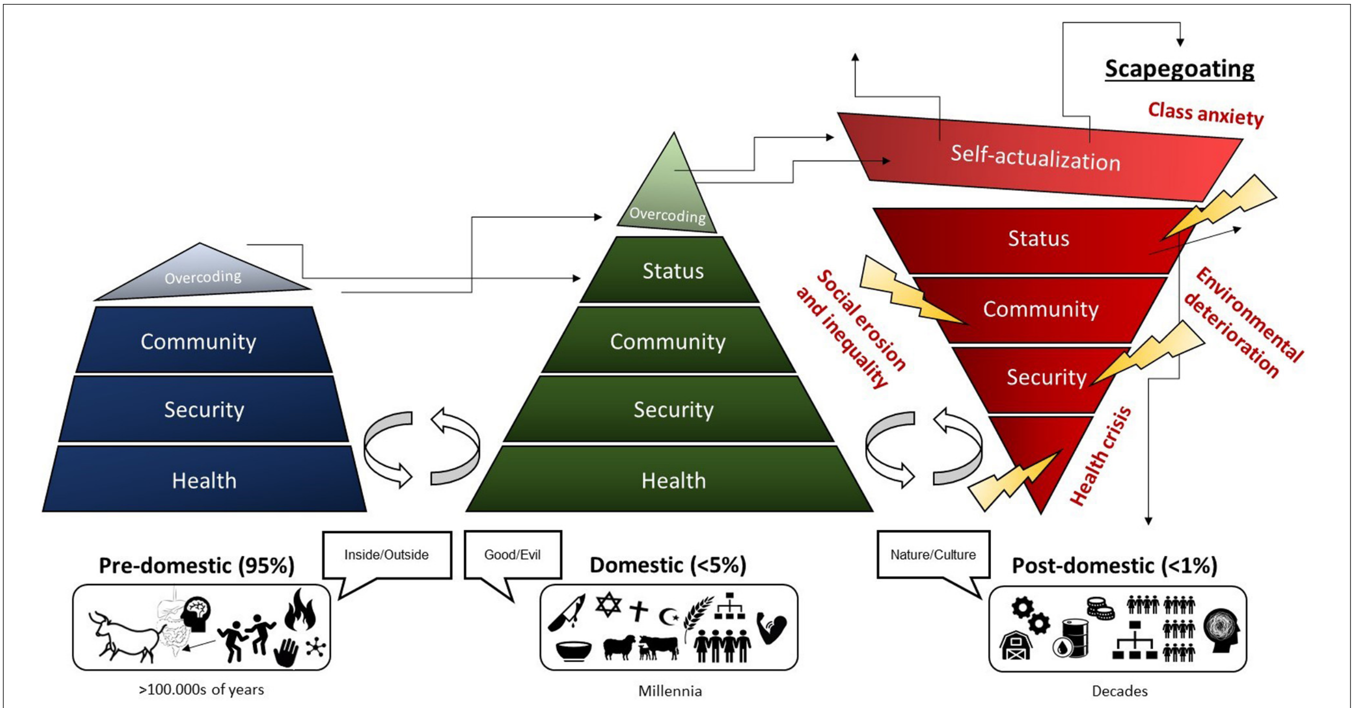

FIGURE 1 | Schematic overview of the transitioning of biosocial needs for animals in human foodscapes and thoughtscapes.

entails cooperative benefits and risk minimization (Wilkinson and Pickett, 2010; Leroy and Praet, 2015), but also meets a mental requirement through the collective fulfillment of an *Unschuldskomödie* (Burkert et al., 1987).

The Domestic Era: Livestock and the Construction of Hierarchy

As the Mesolithic came to an end, a flexible model of hunting, fishing, foraging, agriculture, and animal husbandry appeared, for instance in the Mesopotamian wetlands (Scott, 2017). A disruptive moment was reached some 6,000 years ago, likely due to ecological constraints, which led to settling, resource accumulation, and the formation of the political state. A novel bureaucratic, tax-driven, and cereal-dependent system of domestication (of both humans and animals) engendered an increased hierarchy and the formation of elites (Scott, 2017; Christakis, 2019). In parallel, human–animal interactions evolved from reciprocity to dominion (Leroy and Praet, 2017). Animals were used to confer social status; for instance, during the ritualized act of sacrifice (**Figure 1**). It has been speculated that the first collection of meat and milk was for ceremonial rather than nutritional purposes, developing unanticipated benefits (Bulliet, 2005). The collection of milk in skin bags for libations may then have led to the discovery of dairy products. In addition, animals were mobilized for the plowing and fertilization of cropland, the utilization of otherwise infertile lands, and the myriad of other functions that followed their new role as livestock. Because the reliance on ritualized sacrifice in Neolithic societies is a recurrent element that appears to have left persistent traces in the cultural blueprint of human civilization, its role in human–animal interactions deserves a closer look.

The transition from foraging to settled agriculture increased the amount of people that could be supported per hectare of land from 10^{-4} to one person per hectare (Smil, 2019). When the 'natural' size limit (±150; cf. Dunbar, 1998) of hunter-gatherer bands was exceeded, a need for more hierarchy surfaced to prevent destabilization of the social order. Whereas desire for status is not all that pronounced in the rather egalitarian context of hunter-gatherer communities, mostly involving 'costly signaling' by hunters, its importance increased in settled, larger, and more structured societies. In the latter, status is built around resource accumulation (e.g., ownership of animals for plowing; Kohler et al., 2017). What was a gift of nature became incorporated in a property regime, while the concept of 'nature' evolved into that of 'natural resource' (Scott, 1998). In contrast to the elites, the lower classes had little access to animal foods, resulting in malnutrition (Smil, 2019). At the same time, in these centralized agricultural systems, power was administered through the visible language of record-keeping systems based on grain as both material foodstuff and numerical abstraction (Scott, 1998). Grain – as a commodity that could be stored for indefinite periods of time and as the basis for concepts related to numeracy – anchored the power of elites through record-keeping and the distribution of staple foods (Schmandt-Besserat, 1986). Here, we see how control of the food system as a form of authority does not merely reside in the control of food, but also in the symbols related to food and their place in thoughtscapes. Hierarchical centers, such as the Roman Empire or the Zhou dynasty, portrayed the eating of meat and dairy as 'barbarian.' Such discourse was meant to maintain crowds within state boundaries, as the agroeconomic grain-and-manpower core was the basis for the generation of wealth (Scott, 2017).

Strong social heterogeneity requires highly effective mechanisms for stabilization. According to Girard (1986), the problem is reinforced by *mimetic desire*. In the words of Girard: 'Man is the creature who does not know what to desire, and he turns to others in order to make up his mind. We desire what others desire because we imitate their desires' (Burkert et al., 1987). It may not so much be inequality as such that is corrosive to group cohesion but the display of wealth (Christakis, 2019). Elites attract venerating imitators ('be like me, value the object'), which are then rejected ('do not be like me, it is mine') (Burkert et al., 1987). In the absence of apotropaic rituals, this results in intraspecific aggression, retaliation, and endemic violence. The latter can be stopped only by a pacifying act of 'final killing,' which relies on the scapegoating and sacrifice of a surrogate victim. A scapegoat needs to meet certain requirements; it must be recognized as the guilty Other and be unable to retaliate. By redirecting aggression upon the victim, difference is dissipated while dramatized rituals displace guilt and mask the arbitrariness of the act (Burkert et al., 1987). Ritual sacrifice functions as a mechanism to dispel crisis caused by societal class struggle and other anxieties (e.g., the uncertainty of harvest success), thus contributing to a community's symbolic systems. It is relatively clear that animal sacrifice and scapegoating became a widespread practice, but much less so if animals acted as a late substitute for humans. René Girard takes a hard position by surmising that human sacrifice was 'the first symbolic sign ever invented by hominids, instrumental in the transition from an undifferentiated human–animal past' (Girard et al., 2008). Be that as it may, the scapegoating and ritual killing of animals have entrenched themselves as statutory practices in the mythological and religious schemes of early human civilizations (cf. Bakker, 2013), with enduring results over the next millennia.

The Post-domestic Era: From Zoophage to Sarcophage

Although the domestication template for human–animal interactions displays a vast amount of cultural and practical diversity throughout history, its dominion-based premises have remained relatively robust until the use of fossil fuels in the 19th century (Scott, 2017). Deep societal change took place during the post-domestic shift, particularly so in the Anglosphere and later also becoming more widespread in Europe and other parts of the world. Besides such historical elements as the role of meat in class struggle (Horowitz et al., 2004), the transition can be ascribed to modernity's disruptive infrastructural and technological innovations, allowing a surge in meat supply to meet the demands of urbanizing populations (Leroy and Degreef, 2015).

Thus, basic (food) security became almost self-evident in the middle and upper classes of Western societies. With foodscapes reaching abundancy, a search for new purpose-offering challenges was initiated. Within the biosocial needs complex, the post-domestic 'self-actualization' level reflects an urge for identarian expression and related habitus and aesthetics (**Figure 1**). The further one moves up the social ladder, the more one achieves a sense of self-confidence to do so (Wilkinson and Pickett, 2010). Although the desire for in-group solidarity and status are still latent and continue to be a source of anxiety, they manifest themselves in novel ways whereby the eating of meat is used to opinionate on tradition, hospitality, and/or identity. As such, display of the type and quantity of meat one eats (or does not eat) still conveys information about one's economic and cultural capital (cf. Bourdieu, 1984), but can also signify genuine intellectual investment (Leroy, 2019).

The removal of livestock from civic life and the introduction of domestic pets went hand in hand with a novel set of practices and discourses. Upon demand by the bourgeoisie, explicit references to raw animality, including birth, copulation, and death, were suppressed; livestock was blamed for corrupting the youth so that its 'monstrosities' (blood, gore, and smells) had to be removed from public life (Bulliet, 2005). This illustrates not only the West's expanding views on what constitutes trauma (Haslam, 2016), but also points to a *pharmakos*-type 'ban,' outside the city walls and into the slaughterhouses, a process starting in the 19th century (Leroy and Degreef, 2015). The pharmakos (φαρμακός) refers to a human scapegoat in ancient Greece, chosen based on 'ugliness' and sacrificed as a means of purification or atonement for the community (Burkert et al., 1987). The scapegoat was tortured, driven out of town, and possibly killed.

Although intimate and daily human–animal interactions with livestock are still the norm in rural communities worldwide, including the family farms of the West, the situation is very different in the most intensified parts of animal agriculture (McCance, 2013). With most of the butchering of animals now being concealed or abstracted, the post-domestic and urbanized public is left in a state of disconnect and quasi-denial (Rothgerber, 2019). While animal source foods were reduced to the status of commodities in a general process of de-ritualization and de-mystification (Bulliet, 2005), humans transitioned from *zoophage* ('eater of animals') to *sarcophage* ('eater of meat') behavior (Leroy and Praet, 2017). The post-domestic crisis, described below, seems to be adding a novel and pejorative category of meat eaters to the global thoughtscape: the *necrophage* ('eater of death').

THE POST-DOMESTIC CRISIS

Post-domestic Sensibilities to Animal Killing

The post-domestic model retained its metastable functionality until recently. In the current age of mass media-based (dis)information (cf. Leroy et al., 2018), the unprepared model is put to the test. As the disconcerting acts of animal killing and butchering are no longer incorporated in a sound cultural framework, their impromptu display has become problematic (Leroy and Praet, 2017). When meat is seen as a 'corpse' and death as a 'contaminating essence,' physical discomfort and disgust are the result (Testoni et al., 2017). This is particularly the case for the young urban generations that are, historically speaking, probably the ones most disconnected from praxis. According to Bulliet (2005), the disappearance of exposure to scenes of slaughter and animal copulation from childhood experience has created post-domestic sensibilities, especially in post-World War II generations. Meanwhile, animals have been anthropomorphized and *cutified* in popular culture. This evolution is a product of bourgeois pet-keeping culture, which evolved into a mainstream practice (about two-thirds of the American households now keep pets and spend more than sixty billion dollars a year on their care; Christakis, 2019). Fantasy is put in the place of real-life carnality, so that viscerally powerful encounters with either sex or slaughter during later stages of life may lead to shock. Petracci et al. (2018) mention examples of outrage when the public is confronted with the butchering of rabbits, cute animals *par excellence*. Such profound disengagement understandably leads to distress when emotionally upsetting scenes of slaughter and butchering are shown to a public that has grown accustomed to purchasing packaged, processed, and often pre-prepared and ready-to-eat foods in metropolitan retail (Leroy and Degreef, 2015).

This situation typifies the English-speaking world in particular, especially the United States, United Kingdom, and Australia (Bulliet, 2005). Nonetheless, similar trends are emerging in 'carnivore' Latin America (Argentina, Brazil, Uruguay, Chile, and Colombia), where amorphous hamburgers are overtaking the traditional steaks and asados and, with that, the explicit references to living animals. The fact that the Anglosphere leads this evolution may be linked to the fact that it also displays the strongest suppression of traces of pre-domesticism (Bulliet, 2005), which according to Shepard (1998) leads to an unbalanced mindset. Ancestral traits include all-age access to scenes of butchery, birth, copulation, and death, little accrual of property, absence of domestic animals, and immediate access to the wild and solitude. Shepard (1998) argues that a pre-domestic thoughtscape is a far cry from the post-domestic attempts to 'associate feminism, vegetarianism, and animal liberation in [a] historical or anthropological framework.' This is, of course, a very idiosyncratic view on humanity bound to generate controversy. As stated by Bulliet (2005): 'in post-domestic circles there is a war being fought over who defines the nature of primal humanity. The question of separation is embedded in that war, and meat eating is its prime battlefield.'

Societal Anxieties Related to Urgency and Collapse

The current livestock system is depicted as one that casts a 'long shadow' over society (cf. Steinfeld et al., 2006), with strong overtones of urgency and collapse (Pelletier and Tyedmers, 2010). The contextual contingency of animal husbandry on good or bad practice is often narrowed down to a societal narrative that presents it as intrinsically harmful (Leroy and Hite, 2020). Plant agriculture, equally leading to both harmful *and* benign effects, is mostly off the hook. Although presented as part of the solution for a sustainable food system by some (e.g., Gerber et al., 2013), animal production is portrayed as a 'problematic' or even 'evil' act by others (GRAIN/IATP, 2018; Halligan, 2018), whereby its potential for improvement is being downplayed. The crisis is said to be the harmful yet calculable result of unhealthy Western diets and their unsustainable production methods (Poore and Nemecek, 2018; Swinburn et al., 2019; Willett et al., 2019). Societal tissues are degrading (Wilkinson and Pickett, 2010), whilst traditional foodscapes shift to dietary individualism (Rozin et al., 2011; Fischler, 2013); what was once taken for granted suddenly looks problematic, including the provision of reliable nutrition. In the United States, for instance, nine of ten inhabitants are now identified as 'metabolically unhealthy' (Araújo et al., 2019), and the United States is moving toward an even worse public health status (Ward et al., 2019).

There are indisputably significant concerns with the global status of animal production (Steinfeld et al., 2006). Yet, it is remarkable that much of the debate – including the scientific one – is placed along a plant–animal binary (Leroy and Hite, 2020). Plants, such as whole grains, legumes, and nuts, generally represent a virtuous dietary choice, whereas animal foods (red meat in particular) are said to be destructive to both human health and the planet. Much of this discourse is rooted in societal dynamics, including the impact of class anxiety and the moral urge to *eat right*, in pure, natural, and civic ways (Biltekoff, 2013; Veit, 2013; Finn, 2017; Hite, 2019). A Garden-of-Eden image of vegetarianism (Sánchez Sábaté et al., 2016; Testoni et al., 2017), which was shaped in the 19th century by Bible Christians, Grahamites, and Seventh Day Adventists, led to claims that meat is impure and provokes carnal lust. Notions of impurity gained traction in both vulgar and professional dietary discourse during the 20th century, as the superficial narrative moved away from the spiritual and sexual to the medical and environmental (Banta et al., 2018; Leroy and Hite, 2020).

The first edition of the 1977 US Dietary Goals – which influenced all future national public health nutrition policy, both in the United States and elsewhere – specifically called for reduced meat consumption. At the time there was no scientific evidence to justify such a recommendation, but then as now, moral and environmental concerns were overlaid with justifications from weak observational evidence (Hite, 2019). This helped to create a specifically Western 'healthy user bias,' shaping the results of subsequent observational studies that have been used to portray meat as unhealthy. Health-motivated people tend to restrict meat because they were told to do so by health authorities, thereby creating an artifact in the outcomes that are further used to amplify the original message. The fact that this is a cultural lifestyle effect can be deduced from the finding that the associations between meat eating and disease often disappear or invert when measured in a non-US context (Leroy and Cofnas, 2020; see Dehghan et al., 2017 for examples of how animal foods are linked to better health when non-Western populations are surveyed). A recent comprehensive quality assessment of the evidence showed that the current recommendation to reduce meat consumption in order to prevent chronic disease is based on weak evidence with (very) low certainty (Johnston et al., 2020). Meat, still, has an important role to play in healthy diets (Provenza et al., 2015, 2019).

Activation of the Scapegoat Mechanism

Post-domestic subjects become inevitably frustrated when their search for self-actualization reaches its limits and common challenges are lacking (Harinam and Henderson, 2019). At the same time, inequality and income gaps with the elites accumulate (Piketty, 2014), compromising the underlying desire for status (**Figure 1**). Competition over prestige then results in intergroup hostility and prejudice toward outer-groups (Christakis, 2019). The impact of this devastating trend on societal dynamics and wellbeing cannot be overstated (Wilkinson and Pickett, 2010). Although plebeian reactions are often driven by insecurity associated with primary needs (e.g., yellow vests-type movements), middle classes are instead exposed to class anxiety and respond through virtue signaling. Finn (2017) has shown that this typically includes 'moral eating' and the eulogizing of vegetarianism.

In a remarkable transvaluation of values, the meat-causes-harm narrative is used to invert what was historically seen as representing strength, life, sensuality, abundance, hospitality, taste, and normality, into deterioration, death, infertility, debauchery, selfishness, disgust, and abnormality (Leroy, 2019). Due to the moral crisis within the bourgeoisie, absolute standards of excellence become less active than the belittlement of non-conformists and 'oppressors' (either real or imaginary). Feelings of *ressentiment* (cf. the psychology of the Master-Slave question; Nietzsche, 1887) also trigger introspection, leading to an ascetic regimen of self-surveillance and the cultivation of the quiet virtues of the herd (patience, obedience, cooperation, and perseverance). In such a context, primal instincts, appetites, and vitality are portrayed as sinful signs of a flawed 'animal' nature (Conway, 2015).

Given the rise in social tensions, an activation of mob behavior and scapegoating mechanisms does not come as a surprise (Girard, 1986). The naming of a surrogate victim creates a unifying narrative and the abolishment of *difference*. Mobs are typically characterized by deindividuation (Christakis, 2019). Usually, the pharmakos concept also entails that of the *pharmakon* (φάρμακον; i.e., what is poison *and* cure). Potential scapegoats not only need to match the pharmakos/pharmakon criteria, but also need to stand out due to the differentiating peculiarities and stereotypes that construct the common 'Other' (Girard, 1986). Livestock, with its longstanding role as societal insider/outsider, is an obvious candidate. All this is evocative of Hathor, an Egyptian fertility goddess with an earthly presence as dairy cow *and* a blood-thirsty demon unleashed by Ra to punish humans for their sins, toppling cities and tearing up fields. Cattle provide nourishment and build soil but are also depicted as causing disease and ecosystem destruction due to overgrazing and methane belching. Humans are sinful for indulging in meat and dairy, which are portrayed as unnecessary luxuries. Moreover, animal source foods have been portrayed as a pharmakon in mass media over the last decades (Leroy et al., 2018), being both healthy *and* unhealthy, so that their peculiarities can readily be converted into the monstrosities of the pharmakos, contrasting with the homogenic purity of the mob. References to blood, manure, cow farts and belches, 'chicken periods,' and 'milk pus' aim at collapsing the play of meaning to the 'livestock is harmful' side of the binary.

As a result, eating animal source foods is increasingly presented as an immoral search for luxury and pleasure and as a selfish act undermining societal prosperity. The post-domestic crisis thus opens the door to outrage culture (Harinam and Henderson, 2019), whereby the mundane (*in casu* eating) becomes a calamity in the face of crisis. On a more positive note, this may help to overcome the existential problem of Western complacency by offering challenges that create group solidarity and generate new meaning. Future 'scapes', whether they aim at abolishing or creatively re-defining the role of livestock, will have to address this point (**Figure 2**). In any case, when it comes to a search for healthier societal foundations, a return to communion, commensality, and conviviality may well be one of the most powerful options that we have at our disposition (Wilkinson and Pickett, 2010; Halpern, 2012; Fischler, 2013).

THE CASE FOR A GREAT TRANSITION: THE ABOLISHMENT OF LIVESTOCK AND ITS IMPLICATIONS

A Radical Response to a Moral Crisis

A conflict between foodscapes and thoughtscapes has become evident to those post-domestic subjects who are no longer able to robustly align the historical 'need' for animal foods with the requirements for animal rearing and killing (Benningstad and Kunst, 2020). Selective exposure to the most graphic and problematic examples of today's industrial livestock production have amplified this effect and resulted in a mental crisis. Such scenes focus on concentrated animal feeding operations, the debeaking of poultry and tail-docking of pigs, fast-track mass-slaughter packing facilities, etc. (McCance, 2013). The issue has become more acute even during the last decade due to animal rights campaigns on social media, Netflix movies, and supportive celebrities (Jallinoja et al., 2019). A radical response to this crisis, at least on a theoretical level, would consist of the *abolishment* of hunting and animal husbandry, leading to institutionalized veganism, rewilding of agricultural land, and the end of 'speciesism' (Deckers, 2016). In principle, this offers opportunities to actively readdress humanity's biosocial needs (**Figure 2**), including the use of 'plant-only' eating to potentially achieve health improvement (Kahleova et al., 2017) and nutritional security (Shepon et al., 2018) and to promote feelings of social belonging and self-identity (Jallinoja et al., 2019), often on a spiritual basis involving 'purity' or other transcendental values (Testoni et al., 2017). Status aspirations can be met through virtue signaling or similar social distinctions, such as access to 'cruelty-free sex' (Potts and White, 2007) or claims on the authenticity of one's vegan lifestyle (Greenebaum, 2012).

The Great Food Transformation: What's in a Name and Where Is It Coming From?

As unlikely as this may still have appeared in the late 20th century, the prospect of a (near-)vegan global society is now a respectable part of the conversation in influential circles, among certain media (Leroy et al., 2018), celebrities (Doyle, 2016), academics

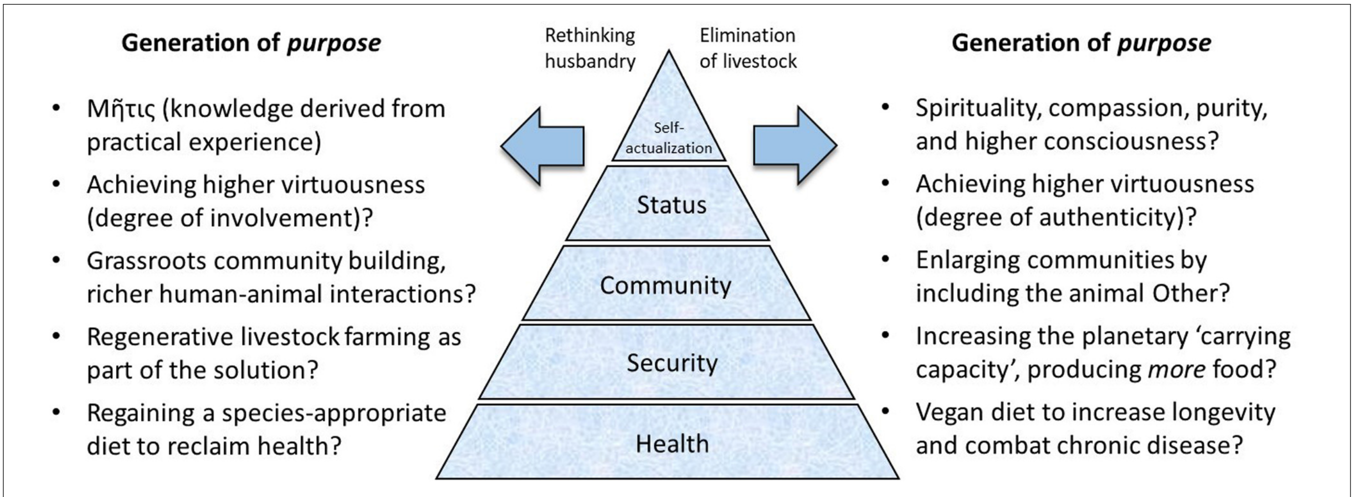

FIGURE 2 | Fulfillment of biosocial needs through reimagined human-animal interactions, according to two potential scenarios for future foodscapes and thoughtscapes.

(Deckers, 2016), and entrepreneurs[1], who wish to make plant-only eating 'permanent, instead of just a passing trend' (Flink, 2018). A societal tipping point is being aimed at, particularly so within the millennial and younger generations. The concept of tipping point implies that a majority opinion in a population can be reversed by a small fraction of proselytizing agents, when growing beyond a critical population threshold of about 10% (Xie et al., 2011). Current levels of veganism are still low (1–4%), although vegetarianism is able to reach a 10%-representation among young females and is often looked upon sympathetically by flexitarians (Jallinoja et al., 2019).

To reach enough critical mass, the influencing of policy makers is essential (Anonymous, 2020). Pleas for a 'Great Food Transformation' could create such momentum (Lucas and Horton, 2019). Although tolerating minor fractions of animal foods, its so-called Planetary Health Diet also approves of a vegan variant. The diet was designed by the EAT-Lancet Commission (Willett et al., 2019), which argues, together with its close affiliates (e.g., the World Resources Institute, WRI), for hard policy interventions. The latter potentially include a severe tax on meat (Anonymous, 2018; Springmann et al., 2018) or its banning from menus (Ranganathan et al., 2016; Vella, 2018).

Despite being heavily criticized for its scientific and pragmatic premises (e.g., Bloch, 2019; Gebreyohannes, 2019; Mitloehner, 2019; Provenza et al., 2019; Torjesen, 2019; Tuomisto, 2019; Zagmutt et al., 2019, 2020; Leroy and Cofnas, 2020), the EAT-Lancet diet has backers in prominent positions, such as the World Business Council for Sustainable Development (WBCSD, 2020a), the United Nations (e.g., Un News, 2019), and the World Economic Forum (WEF; e.g., Whiting, 2019). The EAT network is supportive of food multinationals that display a particular interest in the 'plant-based' and vegan market (cf. Gretler, 2018; Wood, 2018; Kowitt, 2019) and industrial players with even more extreme anti-livestock agendas, such as Beyond Meat and Impossible Foods. The latter two companies envisage the *elimination* of animal foods from the human diet by the year 2030–2035 (Levitt, 2017; Garcia, 2019) and have received the 'highest environmental honor' from the UN Environment Programme (UNEP, 2018); Impossible Foods also won the UN's Global Climate Action Award (UNFCCC, 2019). The founder of Impossible Foods has stated that the company plans 'to take a double-digit portion of the beef market within 5 years' so that it can 'push that industry, which is fragile and has low margins, into a death spiral.' Next, it will just have to 'point to the pork industry and the chicken industry and [. . .] they'll go bankrupt even faster' (Friend, 2019). Not directly linked, yet characteristic for this mindset of tech-fixing, is the following quote from the United Kingdom-based think tank RethinkX (2019), looking into a 'new operating system for humanity' through disruptive technological interventions: 'By 2030, demand for cow products will have fallen by 70%. Before we reach this point, the United States cattle industry will be effectively bankrupt. By 2035, demand for cow products will have shrunk by 80–90%. Other livestock markets such as chicken, pig, and fish will follow a similar trajectory.'

Recently, a Global Commons Alliance (GCA[2]) was constituted, consisting of the EAT foundation and several of its allies (WBCSD, WEF, WRI, and UNEP), as well as various business platforms (e.g., the Natural Capital Coalition, We Mean Business Coalition, and Ceres). The GCA is tightly associated with the Food and Land Use Coalition, which proposes – among other measures – a >90%-decrease of red meat for Australians by 2050 (Navarro-Garcia et al., 2019), as well as with the business-linked C40 Cities initiative. The latter reported dietary exclusion of meat and dairy as one of its 'ambitious targets' (C40 Cities, 2019a) and has obtained approval from the mayors of fourteen global cities, aiming for the achievement of the Planetary Health Diet for their citizens by 2030 (C40 Cities,

[1] http://veganleaders.com

[2] http://globalcommonsalliance.org

2019b,c). The mayors' political influence will be mobilized and business actions activated, such as the promotion of 'plant-based hamburgers, [adjustment of] supermarket or web designs, such as vegetarian sections, [use of] household smart devices to give consumers live feedback about their dietary choices, [and the request for employers to remove] meat within the premises they own or manage, such as canteens or food courts, or by not allowing employees to expense meat-based meals.'

The conditions of possibility for such a radical yet far-reaching design can be discerned from the past record of its main participants. EAT's founder, the Stockholm Resilience Centre (SRC), is a joint initiative of Stockholm University, the Beijer Institute, and the Stockholm Environment Institute (SEI). The SEI was named after the UN's 1972 Stockholm Conference on the Human Environment, organized by Maurice Strong. As an oil and mineral businessman and a promotor of 'business solutions' to the environmental crisis, Strong also was instrumental in the foundation of the WBCSD, prior to the Earth Summit in 1992 (WBCSD, 2020b). This formed the basis for a global management elite wishing to approach the environmental crisis as a profitable enterprise, thereby co-opting leading NGOs (Chatterjee and Finger, 1994). To enable a high modernist society governed by technological principles, a 'sustainable development' ideology was required. In 1995, SEI joined the Tellus Institute in setting up a Global Scenario Group in support of so-called Great Transitions toward a novel, 'planetary phase' of civilization[3]. The Tellus Institute counts the founder of WRI amongst its Associate Fellows and co-founded yet another corporative platform[4]. This framework was used to feed the Global Environment Outlook series from UNEP, and the work has since been continued by the Great Transition Initiative (GTI). The Great Food Transformation is therefore to be considered as one of the Great Transitions, not only based on the denomination but also on the actors promoting it.

The GTI often has an outspoken esoteric dimension, as in its commentary on the 'Great Unraveling' and the spiritual side of the Earth Charter (Rockefeller, 2015). This is in line with the eco-spiritual legacy of Strong (Chatterjee and Finger, 1994), who besides being a businessman also founded the Manitou Foundation[5] and was close to the Lindisfarne Association, both icons of the New Age movement. In fact, many of the global managers in Rio's Earth Summit system were members of the New Age church (Chatterjee and Finger, 1994). All this to indicate that one possible outcome of the post-domestic crisis is indeed fundamentally *de-territorializing*.

Potential Implications for Societal Well-Being

The authoritarian Great Food Transformation, and its reliance on hard policies, 'business solutions,' and social-engineering (cf. Ranganathan et al., 2016) is just one pathway to a predominantly 'plant-based' or even 'plants-only' future. More fluid and spontaneous transitions are theoretically possible yet – in our opinion – implausible. As it is unlikely that they would be endorsed by all members of society, it seems inevitable that such sweeping change would have to rely on an institutionalized 'vegan project' that outlaws animal products (cf. Deckers, 2016; a publication supported by one of EAT's main funders, the Wellcome Trust).

As demonstrated by Scott (1998), such high-modernist, top-down planning attempts usually are highly schematic and unscientifically optimistic, expressing rational order in terms of utilitarian simplifications, neatness, and visual esthetics (cf., the Planetary Health Diet or the Planetary Boundaries). Diversity and complexity are reduced to a set of categories to facilitate descriptive summaries, comparisons, and aggregations. As shown in Section "The Great Food Transformation: What's in a Name and Where Is It Coming From?", the carriers of such plans are capital entrepreneurs (e.g., WBCSD members) who rely on state interventions to realize their schemes of commodification. While state benefits relate to enhanced appropriation, monitoring, and control, global capitalism acts as what is arguably the most powerful driver of homogenization. Successful implementation requires a prostrated civil society, which can be made receptive by a general sense of urgency and crisis. Scott (1998) argues that this gives rise to 'progressive' elites who repudiate the past and wish to implement utopian designs, holding particularly sweeping visions of how science may increase control over nature.

Restrictive interventions come, however, with serious trade-offs. In the case of a Great Food Transformation, this includes a repression of dietary freedom and cultural expression (Torjesen, 2019), a complication of other areas of life beyond nutrition (cf. Greenebaum, 2012), and the potential undermining of livelihoods, societal development, environmental resilience, and human health. This article is not the place for a detailed elaboration, but the radical removal of livestock from food systems is likely to fundamentally compromise all these aspects (for context, see for instance FAO, 2018), without necessarily reducing animal suffering (Bobier, 2020; Leroy et al., 2020) or offering game-changing food security or environmental benefits (Peters et al., 2016; White and Hall, 2017; Leroy et al., 2020). Nonetheless, we wish to illustrate our concerns by expounding briefly on the potential harmful effects on human health.

Although theoretically able to meet all nutritional needs when supplemented, vegan food supply risks being less robust (White and Hall, 2017). This is particularly the case for low- and middle-income countries (Hulett et al., 2014; Domínguez-Salas et al., 2019; Adesogan et al., 2020), but also for vulnerable populations in high-income countries (cf. Koebnick et al., 2004; Phillips, 2012; Fayet et al., 2014; Tang and Krebs, 2014; Cofnas, 2019). Moreover, the nutritional challenges for mid-century relate to the provision of high-quality protein (biological value) and a list of micronutrients and other compounds (e.g., DHA, choline, and taurine) that are only or most easily obtained from animal foods due to either higher levels or better bioavailability (Nelson et al., 2018; Leroy and Cofnas, 2020).

It is all-too simply assumed that animal and plant foods are interchangeable on an agricultural (e.g., with respect to land use) as well as a nutritional level (Leroy et al., 2020). As stated by George (1994): 'The assumption that humans can be

[3]https://greattransition.org

[4]https://www.corporation2020.org

[5]http://www.manitou.org

healthy on vegan diets posits a paradigmatic *normal* human as an herbivore [whereas] real people are not interchangeable with a presupposed *ideal* human.' Those abstractions are based on a paradigmatic human, who is male, and are not meaningful when accounting for the increased nutritional needs, especially for high-quality protein sources, of women during pregnancy and nursing. Abstraction into uniform (male) homogeneous citizenship, as assumed by the Planetary Health Diet, is a typical symptom of high modernism meant to facilitate administration and control (Scott, 1998). Such ideas typically originate in societies that represent only a minority of the global population, being 'Western, educated, industrialized, rich, and democratic' (WEIRD; Christakis, 2019).

Along those lines, the need for fortification, supplementation, and medical supervision will favor the industrial food system, not unlike the need for chemical fertilization in animal-free agriculture. The global corporations that provide such solutions in support of the Great Food Transformation and that have partnered with EAT, attest to just that. According to Chatterjee and Finger (1994), multinationals and their supportive institutes such as the World Bank and WEF are already among the 'worst examples of the Northern development strategy' and 'biggest contributors to cultural and environmental destruction in the South.'

Transformational Effects on Foodscape and Thoughtscapes

High modernism is myopic to anything that does not fit its scheme as a commodity or productive asset, bracketing all that remains as ritual or sentimental values (Scott, 1998). Whereas animal husbandry is portrayed as archaic and inefficient, futurists often emphasize the superiority of high-tech approaches. One illustration is the notion of *Food-as-Software*, whereby foods could be 'engineered by scientists at a molecular level and uploaded to databases that can be accessed by food designers anywhere in the world' (RethinkX, 2019). The option of *in vitro* meat is another example (Stephens et al., 2018). Such 'solutions' will eventually be controlled by an industrial complex that is intrinsically antagonistic to all residues of traditional farming, cooking, and eating. Although whole-plant dietary solutions are in principle possible (provided they are supplemented with limiting micronutrients), it is worrying that the most loudly marketed alternatives for animal foods are ultra-processed products fabricated from low-grade materials, such as starch, (soybean) oil, and protein isolates. Processors emphasize symbolic rather than nutritional value, by exploiting a consumerist demand for 'cultural' capital via (lifestyle) branding (Baudrillard, 1970; Ulijaszek et al., 2012). More independent and wholesome vegan approaches will have a low chance of success without financial, political, and logistic support, will have difficulties in feeding the world population, and likely will not be endorsed by the public.

Thus, ambitious 'veganization' of society not only risks leading to a foodscape dominated by (high-tech) industrialized nutritionism, but also to a problematic and conflictive thoughtscape. Adding to the ecofeminist claim that meat eating is an expression of a Machiavellian culture-over-nature, mind-over-body, and masculine-over-feminine power play (Singer, 2017; Mertens et al., 2020), we argue that a vegan society may as well result in *more* emphasis on the nature/culture binary (Leroy et al., 2020). Granting human-like privilege to non-human animals would merely enlarge the sphere of individuals that are positioned *outside* nature and *above* the non-conscious sphere (Plumwood, 2004). This would fail to recognize ecological embeddedness of both human and non-human animals, entailing ecological risk. Agriculture would need to be fenced off to avoid pest control. As such, an even stricter compartmentalization of wildlife (Nature) and urban life (Culture) would be obtained (Leroy et al., 2020). In a radical setup, this could lead to purifying intrusions in the Nature compartment through genetic engineering of carnivores into herbivores (Verchot, 2014) or by phasing out wildlife via sterilization, whilst residual animals would be confined to parks (Moen, 2016) or pet status. Rather than a nature 'red in tooth and claw,' some may even prefer a world *without* animals (Moen, 2016) or a transhumanist evolution into a *bodiless* future with digitalized minds (Gyurko, 2016).

Based on these lines of reasoning, and although we are agnostic about the optimal global levels of animal foods, we advance the argument that a radical, far-reaching vegan response to the post-domestic crisis will not lead to more balanced or ethical food- and thoughtscapes. Despite the alluring prospect of a common societal project, it risks creating frustration and harm rather than revitalizing humanity's biosocial needs. Moreover, tackling a crisis based on assumptions of corporate-driven eco-efficiency (e.g., *in vitro* meat) may lead to disastrous cultural consequences (Chatterjee and Finger, 1994) and future healthscapes.

TOWARD A NEW LIVESTOCK REVOLUTION

More Than Efficiency Gains

The environmental impact of global animal husbandry, even if real and problematic, can still be largely mitigated (Gerber et al., 2013). Although not always well perceived by society, some consider it unwise to argue against *intensification* as a principle, considering the pressure created by population growth and the climate change crisis (Steinfeld and Gerber, 2010). Moreover, as an umbrella concept, it encompasses both sustainable and unsustainable practices (Horrigan et al., 2002; Tittonell, 2014). This does, however, not imply that future scenarios need to develop solely along a productivity rationale without considering other constraints or uncovering more revolutionary pathways to change. In fact, an excessive focus on efficiency leads to systems' fragility (Schiere et al., 2012), which has clearly been demonstrated during the COVID-19 pandemic of 2020, and may entail some of the problems mentioned in Section "The Case for a Great Transition: The Abolishment of Livestock and Its Implications." Most importantly, it would be unable to fully address the fears, hopes, and needs of society. Considering the current epistemic flux, the change in paradigm will have to run deeper. The development of richer human–animal interactions, that move away from the livestock-as-commodity mindset, needs particular attention.

Toward Healthier Food- and Landscapes

In the wider search for more robust approaches to animal husbandry, the potential of a fresh outlook on pastoralism is particularly acclaimed because of its role in ecosystem services and health, including biodiversity, water retention, nutrient cycling, soil improvement, rural development, and animal welfare (Gerber et al., 2013; Provenza et al., 2015; Gregorini et al., 2017; Massy, 2017; Mottet et al., 2018). The major feed used in such systems – forage plants (grasses, legumes, herbs, forbs, and trees) – is unsuitable to humans and derived from pasturelands, grasslands, and rangelands, which are natural and semi-natural, as well as artificial ecosystems that are – in most but not all cases – impractical for cropping (Mottet et al., 2017). Grazing animals in particular generate a range of services to the ecosystems that go beyond the farm or particular landscapes they inhabit (Leroy et al., 2020). They offer, for example, socioecological wealth and resilience, help to preserve high-value habitats, regulate vegetation growth and structure, recycle nutrients, and sequester carbon (Provenza et al., 2015, 2019; Proença and Teixeira, 2019).

Pastoral livestock production systems are nevertheless subject to critique and societal pressures, as they are said to distract from more intensive livestock farming that would lead to higher yield and lower greenhouse gas (GHG) emissions, including a shift from ruminants to monogastrics (Steinfeld and Gerber, 2010). This claim, however, needs to be scrutinized, as pastoralism not only provides wealth and nourishment to societies, but also provides other valuable ecosystem services, as stated above, and has the potential to obtain a neutral carbon balance (Assouma et al., 2019). Moreover, the opening of pastoral lands to rewilding needs careful consideration (Manzano and White, 2019), as it would ultimately lead to an increase in other methanogenic animals that do not significantly contribute to human nutrition and livelihoods (i.e., wild ruminants and termites). Although current domesticated ruminants produce large amounts of CH_4, this may be comparable to historical wildlife (Hristov, 2012; Zimov and Zimov, 2014), with wild herbivores being less efficient in feed conversion (Manzano and White, 2019).

Even if landscape abandonment may well appeal to a Western eulogization of 'Nature,' it will not necessarily ameliorate climate change effects. Furthermore, reductions in GHG emissions due to intensification parallel increased fossil fuel use compared to extensive options. This is not trivial, as livestock-derived CH_4 in natural carbon cycles differs fundamentally from CO_2 mobilized from fossilized carbon; as long as herd sizes and dry matter intake do not increase, the former will not result in global warming, in contrast to the dramatic accumulating effects of the latter long-lived GHG (cf. Allen et al., 2018). Although total global livestock emissions have been estimated at 14.5% based on life cycle analysis, this is driven largely by local inefficiencies, deforestation, and the generation of feed (Leroy et al., 2020). Instead of focusing on an uninformed and *reactive* divestment in animal husbandry and pastoral livestock production systems, due to perceived harms that are based on deceiving aggregate numbers and reductionist metrics (e.g., CO_2-eq per kcal), there is still large potential for such promising and *active* strategies as silvopastoralism, regenerative agriculture, improved animal health, and managed grazing.

Considerable progress can be achieved for monogastrics, by focusing on their potential for recycling food waste and leftovers (Mottet and Tempio, 2017; Van Zanten et al., 2018; Uwizeye et al., 2019), as well as for ruminants, by adjustment of the grazing management and taxonomical and biochemical dietary diversity of ruminants at individual and herd level (Gregorini et al., 2017), improved channeling of waste streams, and better integration in the circular bioeconomy (Fairlie, 2011; Teague et al., 2016; Stanley et al., 2018). Rather than losing grasslands to annual agriculture and biofuel production, this includes working *with* the carbon storage potential of grasslands and rangelands, the added value of trees, the adoption of improved pasture species, better veterinary care, etc., which are also forms of *intensification*, in their own right (Manzano and White, 2019). This offers an entirely different mindset than the linear approach of Cartesian, mechanical thinking. The latter has led to the replacement of traditional cyclic approaches within the food system by powerful yet one-directional innovations, such as the mobilization of non-renewable fossil fuels for the production of chemical fertilizers via the Haber–Bosh process. Such practices, also including the use of pesticides, herbicides, intensive tillage, monoculture cropping, livestock-keeping on fertilized monotonous swards, and exhaustive irrigation, all have the potential to boost yields. Unfortunately, such potential also comes at a cost, with long-term environmental trade-offs and the disruption of ecosystem dynamics, including soil building, nutrient uptake, and symbiotic relations between bacteria, fungi, insects, mammals, and flora (Scott, 1998). From an animal standpoint, these practices may impair animal welfare and wellbeing, increasing physiological stress.

Yet, rather than insisting on a nostalgic return to the *Organic Mind*, knowledge-intensive schemes may be used to overtake the resource-intensive ones (Massy, 2017). This is by no means an anti-technological stance, but rather a plea to venture into new thoughtscapes. In future pastoral spaces, graziers may need to move away from one-dimensional and myopic views of pastoralism, which should no longer exist in isolation from the wider landscape and societal functions and cease to perceive animals as merely a source of meat, fiber, and milk. Alternative future grazing lands will have to be re-imagined. Instead of excessively hegemonic top-down planning schemes, a search for increased resilience-based system designs that focus on higher social and biological diversity should be favored. This will also need to include a more *situational* and *practical* approach to knowledge than is currently the case (based on local knowledge and Μῆτις; cf. Scott, 1998).

Toward a Richer Thoughtscape

New thoughtscapes will have to redefine the meaning of ethical, healthy, and sustainable foodscapes, while offering a more appreciative outlook on the place of human and animal communities therein. In line with Ikerd (2019), the killing of animals 'should never become comfortable [or entail] irreverence or disrespect for the life taken,' whilst the eating of meat should 'remain a matter of culture, conscience, and personal choice.' We do not have the answer on how to achieve this, and the solution is certainly not straightforward (Pilgrim, 2013), but a more mindful approach to what it implies to grow and eat animals seems a minimum requirement. Practical experience, scientific information with minimal bias, active personal investment in food production and preparation, and more communal ways of eating all offer potential. Wider recognition of the nutritional value of animal source foods and the various benefits of grazing for both the animals and society may further contribute to this (Wilkinson et al., 2019). Meanwhile, the transformation of human–animal interactions into a more rewarding configuration can only be achieved if the post-domestic mindset undergoes a catharsis, by removing some of its most problematic elements and assumptions.

Moral claims that are now taken for granted by partial and divisive parts of society, often taken to an eschatological level, will need to be scrutinized. As an example, farming is neither *unnatural* nor against livestock's interests. Although much can be said about some of the animal welfare issues of a part of industrial agriculture, it is unreasonable to assume that animal husbandry in general – and new holistic approaches in particular – cannot provide good life quality per definition (Leroy et al., 2020). It suffices to compare the life of well-treated animals with the ferocious conditions in the wild. When ethical and welfare standards are in place, livestock will receive a decent life, veterinary care, feed during winter, and a fast death (Baggini, 2014). The refusal to accept that animals need to be killed for food points to the alienation of the post-domestic subject, who is no longer able to grasp the dynamics of life and death (Fairlie, 2018). Although numbers are uncertain (Fischer and Lamey, 2018), the death toll of sentient animals for the production of meat may well be much lower than for the crops needed for its substitution, especially due to pest control and the action of harvesting machines (Davis, 2003; Archer, 2011; Bobier, 2020).

In other words, the prevailing moral crisis is related to post-domestic sensibilities and societal dysfunction (as argued above) plus a sinister view on what constitutes nature and life, *sensu lato*. As long as this problematic perspective remains in place, it may be difficult to alter our relationship with animal husbandry. This will prevent a novel, fresh view on the nature of pastoralism and grazing lands as a table where we all – grazing ruminants and humans – eat in communion. Alternatively, one could hypothesize that our current episteme is partially the result of a malignant attitude to human–animal relations. Returning to the quotes by Levi-Strauss and Orwell cited earlier on, animals indeed have a pivotal role at the nexus of foodscapes and thoughtscapes. They may indeed be one of the most effective targets to trigger broad societal change.

Rather than abandoning animal husbandry all together, a more respectful interaction with animals could unlock the new 'mythology' (although the word may be ill-chosen), to which humanity seems to be aspiring. The transformative process may need to be fundamentally artistic: a *story* to tell, a shared language, a community of discourse (Massy, 2017). We already know that husbandry, if done right, stimulates regional and local thoughtscapes of knowledge and identity (Proença and Teixeira, 2019). We may have to take this one step further by using it as a catalyst for societal change and, if possible, connecting it to the various needs of a globalized humanity. These needs encompass enhanced health and security, a richer communal life, a detoxification of the intraspecific tensions, and an aspiration to a more meaningful and integrational existence. Taken together, this brings us back to Maslow (1943)'s assumptions as well as to the suggestion that the full spectrum of our biosocial needs can only be met through the restoration of a more harmonic societal system (Wilkinson and Pickett, 2010). The reason why humans have evolved higher needs is precisely because it allows them to more efficiently satisfy their basic physiological requirements (Christakis, 2019).

CONCLUSION

The present study illustrates the clash between a historically contingent biosocial desire for animal foods and contemporary narratives that portray livestock as damaging to humans, animals, and the planet. It is unclear in which direction the current view on livestock production that is now prevalent in the urban settings of the West (in particular within the Anglosphere), will evolve to absorb this tension between foodscapes and thoughtscapes, and how exactly it will generate *purpose* in a society fragmented by status anxiety and in desperate need of common challenges. According to one radical scenario, livestock would be rendered obsolete as humans adopt a (top-down) vegan societal model. Another option would involve a profound rethinking of the way animal husbandry is performed in future domains, embracing it as part of the solution rather than being at the core of the problem. Evidently, these are two opposite setups whereas the future would more likely lead to a mosaic of business-as-usual practices, 'plant-based' options, and animal farming with strong agroecological principles. In its conclusive version, the vegan scenario would have vast implications on societal organization. Rather than ending up as a wholesome approach, it risks being highjacked by vested interests and totalitarian schemes. It would be particularly difficult to reverse such a situation, once established. By opposing the elimination of animal husbandry and deruminization of grasslands, rangelands, and pasturelands, and the reactive pleas for *less* or *none*, we argue that an affirmative response is to be preferred (a thoughtscape of *more* and *better*). The most promising way forward, in our opinion, would consist of a combination of the best of current animal husbandry and grazing systems design, revitalized by increased bio-circular praxis, and a much richer approach to human–animal–land interactions than is currently the case. 'Problems' of environment, soil, diet, health, and livestock need to be faced positively with the intention to expand, connect, and innovate. Such approach would need to be open, creative, and in search of actualization, whereby humans and animals would work *with* rather than *against* nature.

AUTHOR CONTRIBUTIONS

FL was responsible for the conception of the study and acted as lead author. AH and PG brought in specific expertise (food studies and pastoralism, respectively) and contributed to the writing of the manuscript. All authors contributed to the article and approved the submitted version.

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Understanding Alignments and Mis-Alignments of Values to Better Craft Institutions in the Pastoral Drylands

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Tensions in values between dryland pastoralists and non-pastoralists, and often between pastoralists themselves, are common globally. The re-imagining of grazed landscapes must recognize that current pastoralists have their own visions of what pastoralism does, can and should provide to both themselves and society at large. “Disrupters” may rapidly and permanently alter the social-ecological system but understanding pastoralist visions and values may help highlight effective and ethical mechanisms by which we can gently shift current systems toward socially re-imagined systems. Here we draw on two case studies from grazed dryland landscapes to highlight the ways in which understanding pastoralist values and visions could help with this shift. We choose case studies from contrasting institutional, cultural and economic contexts to better explore fit-for-purpose policy options. The first case study is from the typical and desert steppe of Mongolia, and the second from dryland Australia. Drawing on primary data and the literature, we explore in these contexts: what constitutes a meaningful livelihood for pastoralists? how might these imaginings align (or misalign) with the imaginings of the broader population? what inertia against future societal imaginings might a potential misalignment create? and how might policy provide a push (or pull) against such an inertia? We show that context-specific understandings of pastoralist values and visions can highlight appropriate policy options to encourage the movement of social-ecological systems toward those that are more socially desirable. However, the design of these options requires understanding unique combinations of pastoral and societal values, biophysical parameters and institutional contexts.

Keywords: livelihood, Mongolia, Australia, natural resource management, development, rangeland, social-ecological system

INTRODUCTION

Tensions in land-use related values, that is moral principles shaped by institutions, traditions, cultural beliefs and societal dynamics, are common between dryland pastoralists and other non-pastoral populations (Thebaud and Batterbury, 2001; Yongo et al., 2010). Unrecognized or unaddressed tensions have resulted in poor engagement or outcomes in natural resource management (Bhatnagar et al., 2006; Kearney et al., 2012), power inequities and elite capture of resources (Upton, 2009) and even violence (Thebaud and Batterbury, 2001; Hundie, 2010). The re-imagining of grazed landscapes, as a theme of this Special Edition, must recognize that current pastoralists have their own visions of what pastoralism does, can and should provide to both themselves and society at large, and that this will affect the implementation of livelihood strategies that align, or misalign, with these re-imagined landscapes.

Various institutional mechanisms have sought to bridge tensions in land-use related values between pastoral and non-pastoral interests. For example, payments for ecosystem services have sought to internalize the environmental impacts of pastoral production in a manner that shares costs between livestock producers and consumers (Ulvevadet and Hausner, 2011; Osano et al., 2013). Community based natural resource management, when designed to be inclusionary and participative, has sought to recognize local values and social norms whilst still addressing environmental goals that may better reflect broader societal values. However, such institutional mechanisms often pre-assume pastoralist understandings of meaningful livelihoods, and the values that inform them. The assumption that financial incentives are the most useful lever for changing behavior in the case of payments for ecosystem services has been challenged (Cocklin et al., 2007; Van Hecken and Bastiaensen, 2010; Moon and Cocklin, 2011). Similarly, the notion of spatially and temporally bounded communities with defined and accepted social norms has been critiqued in the case of community based natural resource management (Hogg, 1992; Leach et al., 2009).

Institutions that seek to move grazed landscapes toward socially re-imagined systems must understand the aspirations of pastoralists. Private and public objectives for grazing must be integrated into emerging institutional and market structures, with management of pastoral land seen as a shared, mainstream land management issue for society (MacLeod and McIvor, 2006). "Disrupters" may rapidly and permanently alter the social-ecological system but understanding pastoralist livelihood visions and values may help highlight effective and ethical mechanisms by which we can shift current systems toward those that are socially re-imagined. Drawing on primary data from two case studies and the peer reviewed literature more broadly, we explore: what constitutes a meaningful livelihood for pastoralists? how might these imaginings align (or misalign) with the imaginings of the broader population? what inertia against future societal imaginings might a potential misalignment create? and how might policy provide a push (or pull) against such an inertia?

APPROACH

Theoretical Framing

Livelihoods are comprised of the capabilities, assets (including both material and social) and activities required for a means of living (Chambers and Conway, 1992). The term is recognized as being multidimensional, including economic, political, cultural, social and environmental aspects. A diversity of livelihood activities in a complex bricolage (Scoones, 2009) leads to a diversity of outcomes and outcome pathways, challenging a simplistic understanding of what constitutes livelihood development. However, the ability and opportunities available to cope with multi-level and multi-scaled shocks and stresses affecting stocks and flows of food and cash are an important component of livelihood sustainability (Chambers and Conway, 1992). This is particularly pertinent in complex social-ecological systems (Ostrom, 2019), like those in the pastoral drylands, which are prone to periodic shocks such as extreme weather events.

Development theory and practice increasingly centers on an understanding of livelihood and livelihood development and on the ability to improve people's choices, capability, freedoms and equity (Sen, 1999). The centring of individual choice in livelihood and livelihood development means that what constitutes a "meaningful" livelihood is inherently value-based. Understanding what constitutes a meaningful livelihood therefore requires understanding not only the means that people have to subsist, but also the meanings with which different subsistence strategies are imbued (Taylor, 2002). Uncertainties, such as erratic precipitation, combined with emerging opportunities, influence the ways in which material and non-material resources are used, and on the choices that individuals make between different sets of values that are associated with the use of these resources (Hebinck and Bourdillon, 2002). That is, values ultimately affect material subsistence strategies.

The values and subsequent livelihood strategies of an individual or local community can misalign with the values of society more broadly. Access to the informational, financial and institutional resources required to exercise developmental freedom is necessary for livelihood development (Ribot and Peluso, 2003). Access to many of these resources is controlled or administered by the State and thus tends to privilege societal values over that of special interest groups (see Addison et al., 2019 for examples from Australia). However, it is also the point at which the State can facilitate access to particular resources for the benefit of both livelihood development, and broader societal natural resource goals. That is, it is one way in which the State can help shift land-use toward broader societal goals. Ideally, participative and deliberative processes should be used so that a re-imagined landscape is collectively re-imaged, inclusive of the values and aspirations of those most affected. An important step in such a process is understanding the complex and contextually grounded nature of what constitutes livelihood outcomes, pathways and impacts for local people. This approach also includes a recognition of the way in which the values of local people may be in tension with broader societal values. We now use two pastoral case studies to explore how particular livelihood visions and values can align (or misalign) with broader societal values, and the ways in which institutional levers might better recognize pastoralists' livelihood imaginings.

Data Sources

The Australian case study draws upon the published literature, including Addison and Pavey (2017). The Mongolian case study draws upon the published literature that includes a series of published book chapters: Addison et al. (2020a), Addison et al.

TABLE 1 | Summary of case study areas, including some examples of key biophysical, socioeconomic and value-based characteristics.

	Mongolian steppe	Australian drylands
Key biophysical characteristics	Variable precipitation, exposed to extreme winter weather events, contested levels of grazing-mediated degradation	Highly variable precipitation, mixed or contested levels of grazing-mediated degradation
Key socio-economic characteristics	Non-exclusive tenure with the exception of small areas for use as a winter shelter, poorer livelihoods than urban population in middle income country, non-colonial context, high proportion of national population, remote governance and distance to markets	Exclusive tenure to the level of the household, poorer livelihoods than urban population in wealthy country, colonial context, small proportion of national population, remote governance and distance to markets
Examples of important pastoral values	security, freedom and choice, social relations, social boundary between urban and pastoral, "urban population doesn't understand"	Independence, social boundary between urban and pastoral, speak for own property, "urban population doesn't understand"
Examples of important non-government values	Conservation of productive vegetation and fauna, livelihood development	Biodiversity conservation (especially fauna)
Examples of important urban values	Meat hygiene, reduced sandstorms, pastoralists as holders of culture, pastoralists as unsophisticated	Conservation, multi-use drylands, increased Indigenous rights and recreation, "outback mythology," pastoralism as extractive

(2020b), Bennett et al. (2020), and Brown et al. (2020). Addison et al. (unpub data) consists of a mixture of qualitative and quantitative data from semi-structured interviews with randomly selected pastoralists from Mongolia's steppe region ($n = 102$, year = 2019, provinces = Tuv, Dundgobi, Bulgan, Akhangai, Khentii, Selenge and Sukhbaatar). These surveys were developed after both pilots ($n = 10$) and focus groups ($n = 4$) that focused on understanding pastoralist aspirations, livelihood status, and livelihood challenges.

Case Study Description

A set of specific characteristics underpin the coupled social-ecology of drylands (Stafford Smith, 2008). More obvious characteristics include high climatic variability and unpredictability, and low productivity. However, drylands are also characterized by sparse populations, a small pool of expertise, remote governance and distant markets (Stafford Smith et al., 2007; Stafford Smith, 2008). These characteristics create unequal power dynamics that can both contribute to, and compound, significant tensions between pastoral and non-pastoral populations. These tensions have implications for the development, implementation and compliance with formal institutions, like those seeking to promote pro-conservation livestock management. Here, we choose two dryland case studies that share these characteristics (see **Table 1** for a summary), but differ markedly in land tenure arrangements, market integration and cultural history, to better explore potential interactions between how pastoralists conceptualize a meaningful livelihood, how these might conflict with broader social values, and possible entry points for institutional interventions.

Australian Drylands

Over 70% of Australia's landmass is under pastoral production (Holmes, 2002) with <1% of the population controlling natural resource management in over 60% of the continent (MacLeod and McIvor, 2006). Much of Australia's pastoral land is arid/semi-arid (precipitation $\leq$500 mm per annum) with the north of this region (north of 27°S) experiencing rainfall that is highly variable on a global scale (van Etten, 2009). Most of this land consists of beef cattle grazing on unimproved pastures.

Australia's Human Development Index is amongst the highest in the world (United Nations Development Programme, 2019). It is unclear where dryland pastoralists sit in relation to Australia's overall Index, but Australia's rural and remote population has comparatively higher levels of socioeconomic disadvantage, with lower incomes, fewer years of education, higher rates of disability and relatively poor access to health professionals when compared to the urban population (Australian Bureau of Statistics, 2018). Nevertheless, pastoralists and their families have access to a strong social welfare system that includes, for example, financial support for low income families and educational programmes for remote schooling. Alternative employment options are available nationally, with Australia's unemployment rate currently and historically being relatively low on a global scale (The World Bank, 2019).

Rights to utilize drylands for pastoral purposes are predominately exclusive to the level of an individual or company (Australian Trade Investment Commission, 2020). However, these rights are generally limited to a pastoral land-use and on the whole do not preclude other land-uses such as mining or Indigenous Native Title (except in the Queensland freehold pastoral drylands), particularly in areas that remain "unimproved." In pastoral leasehold areas, the primary responsibility for adequate natural resource management falls on the State. In freehold pastoral areas, the title holder holds ultimate responsibility for natural resource management but pastoralists in both types of tenure are still subject to relevant environmental laws. Despite pastoralism only existing since European colonialism, pastoralists are generally not legally required to manage country in line with Indigenous understandings of land management (such as through use of fire). This is the case even in pastoral leasehold areas under Native Title, a land-use that has increased significantly in recent years.

Many of the drylands, and especially in central and northern areas, are in remote locations with limited transport infrastructure while a summer monsoonal influence in northern areas can influence access to markets. The transport logistics, along with the type of cattle suited to the region, mean that the industry operates in segments that are less integrated with the domestic Australian beef market. Instead the industry is specialized into particular export market segments notably live cattle trade and lean beef export markets.

Direct influence and investment by government in the Australian pastoral drylands has declined, with a shift toward community-based service provision (Hunt, 2003). Individuals have been encouraged to engage in local natural resource management activities (such as Landcare—Landcare Australian, 2020), largely on a voluntary basis. Non-government organizations (NGOs) have invested heavily to address the resource constraints of the government-sponsored conservation estate; many of the most recently acquired pastoral properties are run by NGOs rather than by government-based conservation agencies, though often with government funding.

Mongolian Steppe

Like Australia, over 70% of Mongolia's landmass is used for agriculture, the majority of which is under an extensive pastoral land-use. Precipitation is low, with a mean of 227.3 mm pa (The World Bank Group, 2020). Both the significant intra-annual climatic variability and a latitudinal climatic gradient (Kakinuma et al., 2019) drive differences in pastoral land-use. In northern areas where precipitation is less variable and pasture productivity is higher, pastoralists practice transhumance or are stable geographically. In contrast, in southern areas where pasture productivity is low but also variable, pastoralists are largely nomadic. In both areas, Winter shocks ("*dzuds*") caused by factors such as extremely cold temperatures, deep snow, poor preceding growth periods, overgrazing or a combination of these, occur periodically.

Variations in access to services and markets have also led to differences in human geography. The Human Development Index, which takes a value between zero and one, ranges from 0.664 to 0.695 in pastoral areas, with the highest value for the eastern region and the lowest for the more remote western region (Mongolian Statistical Information Service, 2019). The HDI for Ulaanbaatar for comparison is 0.822 (Mongolian Statistical Information Service, 2019). Average monthly household income is similarly lower in pastoral areas than the national capital. There are high levels of un- or underemployment and lack of alternative employment opportunities in general for pastoralists.

Despite lower incomes in the pastoral sector, pastoralism is a much more significant economic activity in Mongolia than Australia. The sector employs about 285, 000 people in a population of about 3.2 million (Mongolian Statistical Information Service, 2019). Agriculture, of which the majority is pastoralism, contributes about 11% to the gross domestic product. It has also provided a significant livelihood security net to Mongolia, with a mass exodus of people from urban areas absorbed into the pastoral sector during the economic reforms of the 1990s (Mearns, 2004).

The economic reforms of the 1990s also involved the State de-investing from the agricultural sector. Livestock were privatized, but forage access was not. As such, land tenure-related institutions are more reflective of biophysical variability in Mongolia than Australia. Whilst pastoralists can be granted exclusive rights to small plots of land for shelter in Winter, access to pasture is non-exclusive (Addison et al., 2020a). Pastoralists have the legal right to track forage availability within their district and, with agreements between district leaders, outside their district if required by biophysical conditions. Local officials are given significant discretionary powers to manage grazing pressures, although they are often not resourced sufficiently to allow policing. Wealthier international development agencies and non-government organizations have grown to support the pastoral sector, with an additional interest in environmental management and conservation amid growing concerns about livestock numbers.

PASTORALIST AND SOCIAL IMAGININGS: ALIGNMENT AND MISALIGNMENT

Australian Drylands

Despite its relative recentness as a land-use, the Australian population continues to attribute cultural meaning to the maintenance of pastoralism (Holmes, 2002; Hamblin, 2009). Simultaneously, there is both greater societal scrutiny of the land-uses that currently exist (see Russell-Smith and Sangha, 2019 for an example) and an increasing desire for pastoral areas to become more multi-use. Multi-use, in the Australian dryland context, tends to consist of an increased emphasis on biodiversity conservation, outdoor recreation and Indigenous management of country for cultural and environmental outcomes (Quinn, 2001; Hunt, 2003; Russell-Smith and Sangha, 2018). As Maclean (2009) notes, Australia's drylands should be understood as cultural, contested and dynamic spaces. Struggles over land-use are often not over property rights in the legal sense, but rather moralities linked to relationship to land.

Non-pastoralists with a stake in pastoral areas of the Australian drylands have deployed different versions of the "outback mythology," contemporary frontier ideologies that use landscapes as a loci of identity, meaning and belonging, in the general struggle for control of natural resources. The value-orientations of dryland Indigenous people, pastoralists and urban conservationists are incredibly differentiated despite a shared interest in dryland natural resources (Holmes and Day, 1995). In relation to an increased societal interest in conservation, these value orientations, with subsequent implications for livelihood strategies, have often alienated pastoralists from the conservation discussion (Gill, 2003; Addison and Pavey, 2017). This alienation has occurred even in the absence of empirical evidence for their contribution to declining biodiversity. For example, despite the value-driven, widely held belief linking agricultural production and small mammal decline (Williams and Price, 2010), reliable evidence establishing grazing as the primary factor for the loss of biodiversity, rather than a possible contributing factor, is lacking (Fensham et al., 2010; Frank, 2010; Frank et al., 2012; Silcock and Fensham, 2019).

Perceived links between pastoralism and declining biodiversity in dryland Australia have resulted in the greater involvement of conservation NGOs. This involvement has likely exacerbated pastoralist alienation. Many pastoralists perceive that areas taken out of agricultural production for conservation purposes are then poorly managed for biodiversity (Holmes and Day, 1995; O'Connor and Bond, 2012). The cynicism produced by such a practice may both limit the impact of environmental programmes on pastoral land, and undermine confidence in participatory strategies for engaging pastoralists with conservation in off-lease areas (CSIRO, 2003). One example is the pastoral industry's concern over the $9 million given by the Australian government to R. M. Williams for the purchase of Henbury Station in central Australia as a Carbon Sequestration venture. A strong sense of place attachment can render such buy-outs an existential threat to pastoralists (Hunt, 2003). The lack of evidence that such ventures can return a profit, concern over land management, the loss of productive grazing land, and suspicion that the societal emphasis on multi-use values precludes pastoralism, can also create concern (NTCA Open Letter to political parties, July 2012; *Northern Territory Cattlenews* 13(3):9, July 2012):

> *Purchases such as these threaten the long term future of our industry by removing critical mass and skills from the region. They distort the property market because they operate under a different set of rules and with resources not available to other potential purchasers, they prevent new entrants to the industry and they fly in the face of other programs which are intended to encourage on-farm conservation and multiple land use.*

(Rohan Sullivan, NTCA President, Sullivan, 2012).

The livelihood aspirations of dryland pastoralists are complex, encapsulating much more than finances. Russell-Smith and Sangha (2018) found that typical northern pastoral enterprises were unprofitable and carried significant debt as measured by earnings after interest before tax (EABT). Profits are typically much lower than other agricultural communities in Australia (Holmes and Day, 1995). Maclean (2009) also noted that pastoralists in the Tanami Desert face social livelihood challenges including poor access to health and education services, and a high reliance on government assistance subsidies and resources. The strong orientation of dryland pastoralists toward intrinsic, expressive and social values (as opposed to instrumental values where farming is viewed as a means to obtain income and security), and the pastoral lifestyle that provides them with these values, may partially compensate for such continuing economic and social hardships (Holmes and Day, 1995). In particular, an extremely high value is placed on independence (though it is important to note this does not conflict with a strong social orientation).

Pastoralists of Australia's drylands have a strong sense of identity and self-worth. This has flow on effects for what constitutes both a meaningful livelihood, and deployed livelihood strategies. Holmes and Day (1995) noted that South Australian pastoralists closely identify with a distinctive way-of-life and its equally distinctive landscape. This sense of identity is socially "global" with dryland pastoralists comprising a cohesive social group that transcends individual property boundaries. This can often result in pro-environmental behavior, particularly in relation to trans-boundary issues such as the control of weeds, feral animals or fire that may affect neighbors. However, identification with landscape and landscape processes is generally very localized with knowledge about landscape highly specific and place-based (Gill, 1997; Maclean, 2009; Addison and Pavey, 2017). As Gill (1997) notes:

> "*Amongst pastoralists this highly specific knowledge has engendered an ethic that one doesn't talk about anybody else's properties or pass comment on what other pastoralists should or should not do.... To presume to speak for another's property is not only to speak for land you do not know, but is to ride roughshod over the knowledge and experience of another. One does not only transgress property boundaries but also social and personal space. To speak for another's land is to intrude on that person's or family's self. Respect for these boundaries is strong amongst the pastoral community.*" p. 59–60

Dryland pastoralists are very conscious of their custodial role with often a rich and contextually nuanced understanding of ecological dynamics on their property. However, the high value placed on local knowledge accumulated through time can create tensions with the increasing social desire for pastoral drylands to become more multi-use, and to be managed in a particular manner to achieve particular cultural and environmental values. Land management decisions and practices embody cultural epistemologies that are diverse (Maclean, 2009), and mismatched perceptions about landscape ecology, biodiversity, and the appropriate tools and policies for dryland management, have created tension between pastoralists and other stakeholders (Abel et al., 1998; Lankester, 2012).

Specifically, the push toward the incorporation of greater social values throughout specific land management practices are "*transgress*[ing] *property boundaries but also social and personal space*" (Gill, 1997, p. 60) in a way that is considered disrespectful by pastoralists, even if the aspiration of "good" natural resource management is ultimately shared. For example, Addison and Pavey (2017) found that most pastoralists in dryland Australia assigned great conservation value to small mammals, and there was a strong willingness to engage in conservation activities for small mammals that did not conflict strongly with other livestock production goals. However, they also highlighted a potentially significant subpopulation who valued small mammals but did not wish to engage in formal conservation programs due to relationship tensions with potential implementing stakeholders. Amongst a cohort that values independence so highly, poorly thought through social transgression of values risks disengagement from these broader social values, and institutions. Pastoralist emphasis on independence and local knowledge, and distrust of those without these, suggests institutions seeking to encourage pastoralists toward managing for a broader set of values must do so in ways that carefully respect pastoralist knowledge, are brokered by those who are local and trusted, and acknowledge high levels of independence (Addison and Pavey, 2017).

Mongolian Steppe

In Mongolia, the social, cultural and economic importance of dryland pastoralism is so strong as to be enshrined in the country's collective identity (Barcus, 2018); the 1992 Constitution states that "*livestock is the national wealth of the country and subject to State protection*." Unlike Australia, the pastoral and urban population in Mongolia is closely linked through family and friend networks (Sneath, 2006), with pastoralists and pastoral culture still visible in urban areas via annual festivals such as *Naadam*, and the significant *ger* (yurt) suburbs surrounding the capital of Ulaanbaatar. Nevertheless, tensions are growing between pastoral and non-pastoral actors, particularly with the growth in mining, retreat of the State from the pastoral sector and advancement of international organizations in the subsequent vacuum, and the redistribution of the population that accompanied a transition to the market economy (e.g., Barcus, 2018).

Recent decades have led to an increasing divergence in urban and pastoral value orientations (Sneath, 2006). Urban understandings of pastoralists sometimes employ a mythology similar to that of the Australian "outback"; proximity and understanding of nature, pastoralism as strongly underpinning national identity and culture, and with pastoralists hardworking and sincere (Sneath, 2006). However, urban framings of pastoral life are also inconsistent. Negative representations tend to relate to lack of refinement or sophistication, with rural culture disrespected for the same traditionality for which it is applauded (Sneath, 2006).

As in Australia, negative representations of pastoralists also tend to relate to perceptions around extractive or damaging land management practices (Upton, 2020), perceptions that have not always been fully informed by available evidence (e.g., Addison et al., 2012).

Even more so than in Australia, the growing presence of NGOs are both symptomatic of, and drivers of, contestation (Barcus, 2018; Upton, 2020). For example, the tangled intersections of pastoral-related values often manifest strongly where international NGO-sponsored community natural resource management groups have been established. The institutions of community natural resource management groups, even when designed in a participatory manner with pastoralists, often weaken with time or are not strongly acknowledged by those for whom they most strongly relate (Addison et al., 2013). This is perhaps as attempts to strengthen property rights following externally derived understandings of community have created institutional misfits neglecting complex relationships between labor, land, and livestock (Undargaa, 2016).

Mismatched intentions between community based natural resource management design and pastoralist involvement are sometimes underpinned by contestation around the condition, causes of change and the meaning ascribed to changes in the drylands (see Addison et al., 2013). Pastoralists differ in both their perceived contribution to landscape degradation in Mongolia, and the ways in which they believe they can influence grassland condition. In the desert steppe, it is common for pastoralists to emphasize the role of climatic variability on pasture availability rather than overgrazing (Addison et al., 2012). In more densely populated and climatically equilibrial steppe areas, pastoralists are more likely to identify overgrazing as a cause of environmental change but are often unsure as to how they personally may address the issue (Addison unpublished data). Upton (2020) also notes the role of local animist and Buddhist cultural norms and ontologies related to relations of care between pastoralists and the landscape via spiritual entities. Some pastoralists link land degradation to trespass upon these beliefs through, for, example, digging the soil for mining (Addison et al., 2012).

Whilst domestic and international non-government organizations tend to strongly value conservation on the Mongolian steppe (Upton, 2020), the urban domestic population has a more diverse set of values. For example, when Ulaanbaatar residents were asked to choose between attributes related to grassland condition—the proportion of pastoralists in the total population (as an indicator of pastoral culture), sandstorm frequency and meat safety—they were much more concerned with, first, meat safety for human consumption and, secondly, sandstorm frequency than they were with grassland condition (Bennett et al., 2020). For this urban population, and in contrast to NGO values, physical health and safety may be much more important than environmental conservation *per se*.

For the pastoral population, good social relations and security are important aspects of a meaningful livelihood. Addison et al. (2020b) noted the importance of social cohesion, mutual respect, good gender and family relations, and the ability to help others, such as children, for steppe pastoralists. Secure access to natural and other resources, safety, and living in a predictable and controllable environment are considered equally important (also see, for example, Addison et al., 2013; Lkhagvadorj et al., 2013). A primary livelihood strategy resulting from these values is to maximize the absolute number of animals that survive *dzud*, a strategy with empirical support if a pastoralist's ultimate livelihood vision is to continue as a pastoral household (Oniki and Dagys, 2017).

The primacy of the pastoral existence (or, perhaps, subsistence) strategy may well reflect a lack of alternative livelihood options. Whilst many pastoralists may wish for their children to take up alternative livelihoods, many pragmatically note that there are a lack of alternatives (see also Yano, 2012). Mongolian pastoralists emphasize the desire to secure their own children's livelihoods, including assisting them to get an education and profession with some pastoralists wishing their children's professions would be split between the city and herding (Addison et al., 2020b). These desires reflect the mixed perspectives Mongolian pastoralists have toward the sustainability of pastoral livelihoods. Some believe strongly for both cultural and economic reasons in the need for, and viability of, pastoralism in general and for their children. Others are concerned about the high level of livelihood risk associated with pastoralism including production, health and risks of declining resources (Dorjburegdaa et al., 2013). Many external commentators also frequently frame Mongolian pastoralism in terms of an existential crisis (The Economist, 2010; Reuters, 2018).

For many Mongolian pastoralists, freedom and choice are also considered important parts of livelihoods (Addison et al., 2020b), with a pastoral land-use providing them with both. This freedom and choice is akin to the "independence" valued by Australian dryland pastoralists. Likewise, this emphasis on freedom and choice does not necessarily conflict with the high value placed on social relations or social values. Pastoralist-on-pastoralist conflict in relation to access to grazing lands has been frequently cited as being of concern to pastoralists in Mongolia (Addison et al., 2013) with pastoralists often expressing a desire for more pastoralist-to-pastoralist collaboration (Addison et al., 2020b). However, this desire for increased collaboration is unlikely to extend to the urban population; similar to the Australian drylands, there is a social boundary between Mongolian pastoralists, the urban population, non-government organizations and the State that may make policy interventions designed to achieve greater social values in the drylands quite difficult.

RECOGNIZING VALUES AND LIVELIHOOD ASPIRATIONS IN POLICY INTERVENTIONS

As these two case studies illustrate, pre-existing values and understandings of a meaningful livelihood amongst pastoralists tend to involve independence, security, risk aversion and longevity as pastoralists. These values directly inform livelihood strategies that can misalign with broader social values for the drylands. Formal institutions seeking to encourage pastoralists to manage for these broader social values must appreciate the strong emphasis on values other than profit maximization, and be brokered by those who are local and trusted.

Various policy mechanisms have been introduced in dryland Australia and Mongolia to increase socially desired values, primarily environmental services, with limited results. Carrot ("persuasion") and stick ("penalty") policy controls were, and still often are, considered to be important tools for addressing degradation issues in areas under a pastoral land-use with perceived benefits including fully specified solutions, and straightforward monitoring and compliance (Sahl and Bernstein, 1995). In Mongolia, and to a lesser extent Australia, a strong involvement by the State was historically accompanied by significant levels of support such as subsidized mobility and fodder provision in Mongolia's case. Whilst Mongolia's grassland condition is believed to have declined since the 1990s (Addison et al., 2012), with mixed trends in the Australian drylands (Bastin and the ACRIS Management Committee, 2008), internationally these types of institutional tools have tended to produce limited results, with weaknesses including rigidity, oversimplification, lack of adaptability and inefficiency (Sahl and Bernstein, 1995). In the drylands where climatic variability is high and populations are sparse, these constraints have been particularly strong.

More recent institutions that devolve responsibility over natural resource management to the level of the individual or local community have also produced mixed results. Community based natural resource management institutions attempt to promote strong relations between pastoralists, and there is some evidence that social benefits have ensured from these institutions in Mongolia (Fernandez-Gimenez et al., 2015; Ulambayar et al., 2017; Ulambayar and Fernandez-Gimenez, 2019). However, known constraints such as volunteer burn-out (e.g., Byron et al., 2011), perceived inability to translate group activities into demonstrable landscape-level environmental benefits (e.g., Addison et al., 2013; Tennent and Lackie, 2013), multi-level tensions within nested governance systems (Tennent and Lackie, 2013) and a growing conceptualization of environmental degradation as a form of market failure (see Lockie, 2009, 2012), suggest that community based natural resource management alone may not be sufficient.

When choosing whether to become involved in natural resource management, primary producers measure the likely net benefits that a programme or activities will provide pre-existing livelihood goals including material wealth and security, environmental protection/enhancement, social approval/acceptance, personal integrity and ethics, and work/lifestyle balance (see Pannell et al., 2006). Programme design attributes are also important (Pannell et al., 2006; Moon et al., 2012; O'Connor and Bond, 2012; Waudby et al., 2012). In drylands under a pastoral land-use, the implementation of risk-management strategies under a variable climate tends to be orientated toward large herd sizes, lifestyle goals and longer-term economic sustainability rather than short-term profit (Espeland et al., 2020). This suggests that there is an opportunity to better design natural resource management institutions in ways that more accurately reflect pastoralists' pre-existing goals, potentially overcoming some of the weaknesses of prior institutions.

In dryland Australia, the development of institutions that respect pastoralist independence and recognize their autonomy over their pastoral lease may facilitate shift in land-use toward the greater social desire of multi-use rangelands, particularly in the provision of greater environmental services. The potential involvement of pastoralists in small mammal conservation provides an example. The high labor and material costs of conservation in dryland Australia, combined with the high level of spatio-temporal variability of natural resources and threats (Pavey et al., 2017), means pastoralists may be the most cost effective labor source for the temporally strategic management of small mammal refuges during the so-called "early bust" phase of wildlife population cycles. Addison and Pavey (2017) noted that the management of a key threat to small mammals, cat and fox predation, did not conflict with other pastoralist livelihood aspirations and there was a high willingness, and existing action, for pastoralist management of these predators. Reflecting livelihood values being broader than income alone, Addison and Pavey (2017) found that financial incentives did not increase stated willingness to engage with predator control. Instead, strong brokering and support by local "insiders" may provide for the desire for greater State support for conservation management (Waudby et al., 2012) if done so in a manner that respects autonomy and independence.

In Mongolia, whilst various institutions seek to maintain or improve grassland condition through fluctuating seasonal conditions, the devolution of responsibility for managing livelihood risk from the State to individual pastoralists and general retreat of the State from the pastoral sector has meant that local formal institutions supporting pastoralist livelihoods have been weak. Policies that enhance security in the face of high levels of biophysical variability, and promote strong relations between pastoralists, may prove attractive to Mongolian pastoralists, even if they have minimal impact on household wealth. The pilot Payment for Ecosystem Services scheme described by Upton (2020) provides one example of an institutional intervention more cognisant of pastoralist livelihood values. The scheme seeks to link international purchasers of carbon credits with community-based "sellers" of carbon; in Mongolia's case a pasture user group committed to changing herd management in ways that increase stored carbon. To re-frame Upton (2020), a carbon based Payment for Ecosystem Services institution may exploit an alignment between pastoralist livelihood aspirations unrelated to carbon, and the carbon related values of the international community. By being community-based and "bottom-up," rather than targeted at the level of the individual, it may also strengthen pastoralist relations whilst still providing the informational and financial support needed to initiate and maintain the changes in herd management needed to improve environmental services. As Upton (2020) noted, non-monetary incentives such as participation in governance were considered at least as important to many pastoralists involved in the pilot as the potential payments themselves. These features of importance to pastoralists are likely to take on more prominence in future land use policies. For instance Brown et al. (2020) explore pastoralists' stated responses to a cap and trade livestock scheme. In recognition of the querying of what constitutes community in pastoral drylands (Hogg, 1992), such a scheme may allow for some level of collective responsibility and cohesion (in the setting of the overall cap) but also acknowledge and facilitate individual actions and values (in deciding whether to buy or sell more or less quota). The design of such instruments would be crucial in determining whether they do align with pastoralist values as well as their effectiveness in dealing with landscape condition and pastoralist livelihoods.

CONCLUSION

In drylands under a pastoral-land-use, geographical factors like high levels of climatic variability and sparse populations combine with social factors like high levels of independence to mean that pastoralist understandings of "the good life" can relate more to livelihood security and autonomy than immediate material wealth. These values can misalign with the imaginings of the non-pastoral population for drylands that are managed for a broader set of values, such as conservation or meat safety. Engagement with institutions designed to fulfill broader social values are dependent upon the ability of these institutions to help pastoralists meet their value-based livelihood goals. Whilst there may be striking commonalities in values between pastoral groups, context-specific understandings of pastoralist values and visions can highlight appropriate policy options that may shift social-ecological systems toward those that are more socially desirable, with the design of these options requiring an understanding of unique combinations of pastoral and societal values, biophysical parameters and institutional contexts.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Queensland Human Research Ethics Committee 2017000180. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

JA led the drafting of the manuscript, design, data collection and analysis for Australian case study, design and analysis of Mongolian case study. CB contributed to writing manuscript, contribution of intellectual property in the Mongolian case study, project manager of Mongolian case study project. CP contributed to writing manuscript, contribution of intellectual property in the Australian case study, project manager of Australian case study project. E-OL co-design of Mongolian case study contributed to writing manuscript, project coordination of Mongolian case study. DB co-design of Mongolian case study, data collection and analysis for Mongolian case study, project coordination of Mongolian case study. LD co-design of Mongolian case study, data collection for Mongolian case study. All authors contributed to the article and approved the submitted version.

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Controversies and Common Ground in Wild and Domestic Fine Fiber Production in Argentina

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This work analyzes possible obstacles to developing new products or old merchandise using an innovative method. It will look into stakeholders of fine fiber and meat products from three distinctive socioecological systems. Through three case studies, we explore how natural resources management is connected to interests, values, and knowledge by stakeholders, which include government, the scientific community, and people with rural livelihoods. The government vertex is the national and provincial authorities involved with decision-makers at the national and provincial level. The Scientific-Technological vertex includes researchers from INTA, CONICET, and Universities. Rural livelihoods include livestock keepers, farmers, and local people with traditional knowledge. We will address the goods and services provided by two species of wild camelids and domestic livestock. The three cases have both similarities and differences in their focus and common ground of controversial spaces. They create complex networks of relationships and bonds leading to diverse outcomes. Top-down or bottom-up experiences hold distinct epistemology and research consequences, they affect rural livelihoods in various ways. For the three rural livelihoods, meaningful regulations should be endogenous social constructions. However, there are no longitudinal studies on the trajectories of these case studies. Long-term multispecies grazing opportunities are available for the three case studies. It depends on how stakeholders identify flexibility in their common ground to enable resilience to catastrophic events.

Keywords: vicugna, creole goats, guanacos, rangeland management, rural livelihoods, development policy

INTRODUCTION

The innovation and development processes in rural arid and semi-arid environments remain complex issues. They encompass a variety of individuals, groups, and institutions as users of biodiversity. Innovations lead to controversies, tensions, conflicts, and power disputes (León and Aguiar, 1984; UNCCD, 1994; PRODESER, 1997; Hill et al., 2013; Gaitán et al., 2018; García et al., 2019).

The precautionary principle is the backbone of conservation in Latin America. This moral law is widely present in the laws applied to native species. In contrast to this principle, people with rural livelihoods execute decisions based on their previous experience when they consider some native or exotic species as a pest or nuisance. These differences are usually rooted within interests, values, and knowledge of stakeholders (Petitpas and Bonacic, 2019). All actors seem to assign an interest in biodiversity, yet they may not share a common ground. Thus, Controversies among scientists' research approaches and epistemology often develop conflicts and obstacles when these results are applied into biodiversity management decisions, which are crucial for ensuring future human well-being (Quiroga Mendiola, 2013; Easdale et al., 2019; Oliva et al., 2019; Marino et al., 2020).

Vicugna (*Vicugna vicugna*) and guanaco (*Lama guanicoe*) are two closely related wild South American camelids, emblematic to the Andean region. Both species have been described at some point as being on the brink of extinction. For this reason, they were entered, respectively, as Appendices I and II of CITES (Bolcovik and Ramadori, 2006). These two wild species coexist with the domesticated alpaca and llamas. The characterization of genetic resources in domestic and native animal populations is a step toward their conservation and protection.

One of the most powerful drivers of genetic erosion and associated losses of diversity is the overvaluation and excessive use of transboundary breeds over local breeds (FAO, 2007) and habitat fragmentation (Lacy, 1992). Productivity is associated with transboundary commercial breeds and thereby ignoring genotype-environment interactions. This is adequate for hegemonic discourse (Quiroga Mendiola, 2013) or in other words, to the canonization and overvaluation of western science (Fairweather, 2010; Fairweather and Hunt, 2011; Easdale and Domptail, 2014; Easdale and Aguiar, 2018; Kuhlmann and Rip, 2019). Rural livelihoods value their wildlife and local breeds, of traditional and low input systems. However, they find resistance and rejection, describing them as primitive and inefficient by scientists and decision makers. Controversies among the scientific community affect livelihoods, touching the interests and underlying values of all stakeholder groups.

This work analyzes possible obstacles to develop innovative products or old merchandise by a novel method. It will look into the actors of fine fiber production and meat in three distinctive socioecological systems. Identifying large clusters of institutional actors (vertex), controversies, and possible conflicts within and among groups may simplify the development process of special animal fiber production.

APPROACH

Framework for Stakeholders

Countries maintain various institutional arrangements involving government, universities, and industries to develop scientific and technological transformation. Different political histories and traditions create alternative models of innovation systems. Knowledge production and science policy has been discussed through models like the Sabato-Botana Triangle (Sábato, 1975), Triple Helix (Etzkowitz and Leydesdorff, 2000), and Next Generation (Kuhlmann and Rip, 2019). In the agricultural context, Vanclay et al. (2006) analyzed knowledge production from individual farmers' points of view to repertoires for social construction. To analyze collective "common ground" within government, the science community, and rural livelihoods, we identified stakeholders involved in three grazing systems in the context of natural resources **Table 1**. We describe their roles to show controls, tensions, and communications pathways in **Figure 1**.

One vertex of this triangle is the governmental decision-making agencies at the national and provincial level. The second vertex is the scientific and academic knowledge sector, and the third is the rural livelihoods and their commercial organization.

Argentina has a Federal government with 23 provinces, which have full autonomy, as a part of the Nation. The provinces are self-governing, draw up their constitutions, executive, law, and judicial powers, including their own security forces. The national constitution grants the provinces the rights over their natural resources. However, the nation has overall general laws and is responsible for international relations through the various conventions.

The enforcement of natural resources laws is under two different ministries at the national level. The Ministry of Environment and Sustainable Development (MADS) is the enforcement authority for the Convention on Trade International of Endangered Species of Wild Fauna and Flora (CITES) and the Convention of Biodiversity (CBD), including the Nagoya Protocol and the Action Plan against Land Degradation and Drought (PAN, Law N° 24971). National Law N° 22.421 on Wildlife Conservation was passed in 1981, after the first CITES convention in 1980 in response to international conservation concern.

The Ministry of Agriculture, Livestock, Fishing and Food (MAGyP) is the enforcement authority of National Law N° 25.422/01 for "The recovery of sheep husbandry in Patagonia," and "Regime for the recovery, promotion and development of the goat breeding activity," Law N° 26141/06. Relevant to the case studies here is the Ministry of Justice and Human Rights, which enforces the Law of Indigenous Communities (Law N° 23302). Linking this last law and CBD, the Nagoya protocol (2010) promotes and safeguards the fair and equitable benefit sharing derived from utilizing genetic resources (Swiderska et al., 2012). Article 12 opens new communication practices, community protocols and knowledge dialogue. This involves different agencies within national and provincial organizations.

These three ministries of the national government establish general goals related to accounting for sustainability of natural resources jointly with social components. They have clients with diverse needs. The laws are instruments that offer budgets for programs interplaying priorities imposed by international conventions and internal policies, which are enforced by independent institutions. The provinces emulate the national governmental organization, creating an intricate communications network of power relations and exchanges.

The Scientific-Technological vertex is the Instituto Nacional de Tecnologia Agropecuaria (INTA) which depends on MAGyP, the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) that is subordinate to the Ministry of Science, Technology, and Innovation. Public and private Universities rest on the Ministry of Education.

The rural livelihoods vertex comprises farmers, diverse aboriginal communities, livestock keepers and families, grazing their animals in various arid and semi-arid environments. They provide new merchandise or old goods by new methods or traditional knowledge.

TABLE 1 | Summary of case studies.

		Vicugna	Creole Goats	Sheep – Guanacos
Stakeholders	G	MADS: Ministry of Environment (national and provincial) MAGyP: Ministry of Agriculture (national and provincial)	MAGyP: Ministry of Agriculture (national and provincial)	MADS: Ministry of Environment (national and provincial) MAGyP: Ministry of Agriculture (national and provincial) CAP Consejo Agrario Provincial
	R	INTA: Instituto Nacional de Tecnología Agropecuaria CONICET: Consejo Nacional de Investigaciones Científicas y Técnicas, National University of Jujuy VICAM: Vicuñas Camélidos y Ambiente	INTA: Instituto Nacional de Tecnología Agropecuaria CONICET: Consejo Nacional de Investigaciones Científicas y Técnicas, Catholic University of Córdoba	INTA: Instituto Nacional de Tecnología Agropecuaria CONICET: Consejo Nacional de Investigaciones Científicas y Técnicas, CAP Consejo Agrario Provincial
	RL	Aboriginal Communities	Transhumant rural livelihoods	Sheep herders
Focus of Controversy	R	Captive breeding vs. Capture-shearing-release Genetic bottleneck	High productive breeds vs. environmentally adapted local breeds	Multispecies grazing vs. land sparing for guanacos
Differences in Common ground	G	Precautionary principle	Commodities vs. specialty products	Precautionary principle
	R	Overvaluation of science as a producer of knowledge	Overvaluation of science as a producer of knowledge Commodities vs. specialty products	Imposition of urban values on the sense of self-determination of rural lives

G, Government; R, Researchers; RL, Rural livelihoods.

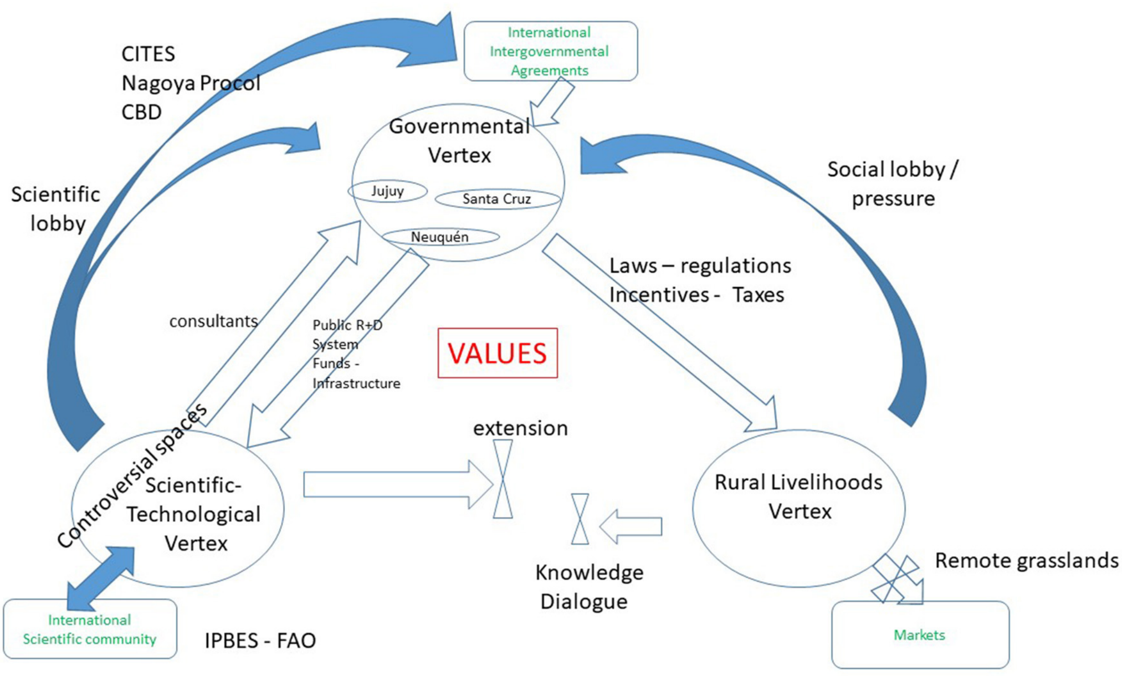

FIGURE 1 | Framework for control tensions and communication pathways.

Controversial Spaces: Focus and Common Ground

Nudler (2004), analyzes controversial spaces in science. According to him, these spaces possess two structural properties: focus and common ground. The "focus" of a controversial space represents its visible region, the tip of an iceberg. The set of visible issues is subject to controversy, discussions, and disagreements. The "common ground" is the underwater portion of the iceberg, invisible to the participants involved in a controversy, and not part of the discussion. The concept of "common ground" synthesizes the set of elements shared and not problematized at any given time (Nudler, 2004; Rodriguez Zoya and Rodriguez Zoya, 2014). According to Nudler (2004), these controversial spaces allow science to evolve. However, this underlying region holds most of the values of societies (i.e., beliefs, concepts of nature, political inclinations, self, and trust). Understanding "common ground" is meaningful for management decisions, which may result in changes of livelihoods.

Controversial spaces are typical to scientific communities (**Table 1**). Disciplines share a common ground with a set of theories, research traditions, and accumulating knowledge leads to scientific technological progress. They discuss their controversies through experiments, data, and debate in a globalized community. These spaces share an established form of communication through publications and the peer review process, by way of which they develop. The domain of their controversial spaces is not necessarily material. In the scientific literature, common ground has different meanings and is used in various ways in diverse contexts. The term is usually understood as shared interests. At this stage, we define common grounds as a set of shared beliefs, values, traditions, art, and emotions. This aspect represents the underwater section of the iceberg, deeply rooted and substantial to existence and the social belonging of researchers.

For example, overgrazing has been the focus of controversy for over 40 years (Bisigato and Bertiller, 1997; Mazzonia and Vazquez, 2009; Gaitán et al., 2018). Recently, Oliva et al. (2019) and Marino et al. (2020) focus on the causes of land degradation is centered on complex socio-ecological drivers. However, many scientists hold overgrazing as the primary cause of biodiversity loss (**Table 1**).

A conflict can be defined as a relation between two or more in opposition, who may or may not be violent, based on differences in needs, interests, and goals. These differences can be real or perceived. Conflict may arise when at least one of the parties is perceived to assert its concerns at the expense of another group's interests. Controversies being at the tip of the iceberg are readily visualized and discussed. On the other side, conflicts lying deeply underwater are usually not discussed or solved, yet they can be managed.

Government communities are a diverse set of people as reflected by an average of 599 provincial and 34 national parties between 2009 and 2019. Participants remain in their positions according to the duration of the government administration. These communities resolve their disputes through lobbying and communication strategies to obtain or remain in power. Rural livelihoods may become the battlefield of the scientific controversial space or conflicts. Conflicts may arise frequently, especially with the local authorities, as their access to decision-making levels is infrequent.

The role of the state in Argentina is frequently under debate. Political parties in government are still a major driving force in research and innovation. The government vertex will include the national and provincial level of authorities involved with decision-making of the cases. The Scientific-Technological Vertex will include INTA, CONICET and the Universities that have researchers related to the cases. Rural livelihoods will contain livestock keepers, farmers, and local actors with traditional knowledge (**Figure 1**). In this paper, we will address the goods provided by two species of wild camelids and domestic livestock.

A bibliographic and existing document review was done for the three cases. Information about laws, values and interests was reviewed emphasizing the search of focus and common ground of actors involved. Available data on the strategies of intervention used in the case studies were compared. Authors have also been in contact with the case studies for about two decades, either as participants or outside observers.

Case Study Sites

The three case studies selected are representative of arid and semi-arid environments in Argentina. They share overgrazing, desertification, loss of biodiversity, and cultural erosion problems. Researchers assign overgrazing as the major production difficulty (Noy-Meir, 1973; UNCCD, 1994; Mazzonia and Vazquez, 2009; Quiroga Mendiola, 2013; Gaitán et al., 2018; Lecuyer et al., 2018). Landscape degradation affects rural livelihoods and is currently recognized as a complex socioecological problem involving desertification and climate change. Aridity and overgrazing have convergent effects on the structure and processes of ecosystems, affecting species richness, abundance of palatable grasses, and soil functioning. Recent research suggests that grazing management should aim to improve species richness and palatable species, to mitigate adverse effects of future increases in aridity on dry lands (Orr et al., 2017; Gaitán et al., 2018; Oliva et al., 2019).

The controversial spaces will be explored within the scientific vertex and the conflicts and tensions between the actors in three different cases as new knowledge evolves into decision-making (**Figure 1**). These case studies center on current conflicts revolving around vicugnas (Vicugna vicugna) in the Puna of Jujuy; transhumant creole goats in the high mountains of Neuquén; and wool sheep—guanacos (Lama guanicoe) in southern Patagonia.

The case studies set in different provinces share governmental complex organization, technological, and regional economic problems. These difficulties are related to systemic barriers in complying with the historical agro-export model based on bulk commodities originated from the pampas production region of Argentina. They have differences in land tenure, their organizational challenges, and diverse cultures.

CASE STUDIES

Vicugnas in the Puna, Province of Jujuy

People in the Puna are mostly aboriginal from kolla, quechua, and omaguaca etnias, closely related to the Andean ayllu and "Customs. "They value" making and deciding among all," linked to agricultural production (Cowan Ros and Nussbaumer, 2013). Culturally, grazing areas are community owned, although some villages are allocated for each family. The Law for Indigenous Communities (Law N° 23302) surveyed 21,300 aborigines in the rural departments of Yavi and Santa Catalina (INDEC, 2010). This law allows them to gain identity and visibility in terms of their cultural civil rights. In order to obtain rights over the land they have used for centuries and now belongs to them, they have to bond as a community. However, the definition of community within the scope of the law is rarely aligned with the local cultural concept (Borghini, 2010; Cowan Ros and Nussbaumer, 2013).

The aboriginal people in the Puna hold mixed flocks of sheep, llamas, donkeys, and goats (INDEC, 2010). Their ancestors domesticated guanacos and vicugnas (Wheeler et al., 2006; Casey et al., 2018). They possess a deep knowledge about these species. Their weaving skill and knowledge to make a fine poncho of vicugna, was acknowledged when it passed through a wedding ring.

Vicugna management has been strongly influenced by international conservationist's pressures. By 1960, populations were at the brink of extinction in all the areas of distribution, i.e., the high Andes of northern of Argentina; Bolivia, Chile, Peru and Ecuador. Populations became isolated and underwent a genetic bottleneck (Wheeler et al., 2006). In 1975, the existing population of vicugnas was categorized in (**Supplementary Material**) of CITES. In 1979, countries with vicugna ratified a convention (Convenio de la Vicugna; CV), which placed conservation, population, and fiber management under strict state control. In 2009 the province of Jujuy passed the provincial Law N° 5634 with a management plan for vicugna. The spirit of the plan was environmental sustainability and socio-economic development. It explicitly incorporates a Committee of eight members, four representing aboriginal communities, two from the science vertex, one from provincial government and one from national government.

In response to international restrictive policies Argentina and Peru, through their scientific—technological vertex, responded with various strategies. Argentina drove a captive breeding program in 1960 at the Experimental Station of Abra Pampa (Jujuy). The aim was to offer productive alternatives to the local communities. This experience was later multiplied in private farms inside and outside vicugna distribution range and was contested by Vicuña Camelidos y Ambiente group (VICAM) (Vila, 2002; Vila and Lichtenstein, 2006). Peru from 1973 to 1980 with German Agency for Technical Cooperation (GTZ) resources started management practices capturing, shearing, and releasing (CSR) wild vicugnas in Pampa Galeras (Peru) with the communities (Hoffmann et al., 1983). Through these experiences Hoffmann et al. (1983) realized that local communities involved in the CV countries are heterogeneous, with differences within and between the communities (Rendon Burgos, 2000). These experiences lead to two controversies.

The first controversy was around the genetic consequences of the captive breeding systems (Vila, 2002; Arzamendia et al., 2008). The studies on the genetic bottleneck of Peru (Wheeler et al., 2006), promoted the controversy. Two laboratories that represented opposed interests concluded that heterozygosity estimates were relatively high for captive and wild vicugna populations of Jujuy (Longo and Valdecantos, 2012; Anello et al., 2016).

The CSR experiences in the province of Jujuy started in 2003. Initially, VICAM researchers developed a top-down experience. The project emphasized teaching adequate procedures to private producers of the Puna, belonging to an Association Cieneguillas (2003–2005) and Santa Catalina Cooperative (2012, 2014) (Bonacic and Gimpel, 2003; Vilá et al., 2010). Initially the project and later reports showed that the conceptual framework was conceived as a top-down experience. The aim of the project was to teach the interested groups how to conduct the CSR activities (Arzamendia et al., 2014; Romero et al., 2017; Cowan, 2019, vicam.org.ar accessed June 2020). This was the starting point of the second controversy.

Neighboring rural livelihoods in Jujuy demanded to develop their own CSR understandings in line with their traditional knowledge (Romero et al., 2017). This was answered by a group of researchers from INTA and local government officials, who from the start used a Participatory Action Research (PAR) approach, which incorporated community empirical knowledge of rural livelihoods. This resulted in a bottom-up collective construction of understanding, which was highly valued as "it meant working together." The process aimed to achieve a flexible CSR protocol adapted to local socio-ecological conditions and allow a learning cycle that positively modifies the environments that affect it (Romero et al., 2017).

As of 2012, the communities of Yavi in Jujuy initiated workshops. They aimed to exchange local traditional knowledge, adaptive management, and scientific knowledge in relation to vicugna administration, conservation, and fiber commerce trade (Romero et al., 2017). The INTA group identified controversies in the communities. Initially, there was a controversy within the residents. One group considered vicugnas as a nuisance, as the population had increased the competition with domestic animals caused economic loss. The other group stated that vicugnas are "sacred creatures," belonging to the Pachamama and should be unavailable for man to benefit from. This was resolved partially after the CSR experience. Members of each community assumed responsibility for taking care of vicugnas in their territory and expressed interest in the sustainable use of the species. The management committee has been endorsed by community assembly formed from Law N° 5634. They set rules like caring for the vicugna meanings that no one should mistreat them, prevent attacks by dogs, and alert of poachers. Some community groups chose to eliminate fences from waterholes to facilitate access to vicuñas. Likewise, some community groups decided to reserve part of the community grassland area for exclusive grazing of vicugnas (Romero et al., 2017; Cowan, 2019).

Vicugnas raw products from captive breeding and CSR sources are to an export company. However, disputes on property rights within the communities and with enforcement authorities have delayed selling fiber (Vilá et al., 2010; Wawrzyk, 2014). For similar reasons, although there is a nearby spinning mill, local development of innovative products is incipient, and the distribution of benefits is unclear.

Transhumance Creole Goats in the High Mountains of Neuquen

The Creole Goats transhumant system originally managed a broader territory than today. Restrictions caused by the political partition between Chile and Argentina (1850) and provincial division disconnecting in 1955 Mendoza from Neuquén. Modern mining, land grabbing, and fencing has reduced grazing areas. Restrictions on the movement on public lands have economic and social integration impacts on these subsistence rural livelihoods (Bendini et al., 2004).

The government vertex implemented provincial policies and regulations that have evolved over the years. In the 1970s, the government passed legislation banning transhumant pastoralism due to concerns around overgrazing and subsequent depletion of resources and environmental threat. This perception continued in the 1980s and promoted two top-down strategies to develop rural livelihoods. One was to convert the transhumance system to that of afforestation with exotic species. The aim was to offer labor through government employment replacing self-employment of the transhumant system (Pérez Centeno, 2001; Bendini et al., 2004). Provincial Government commissioned feasibility studies for Mohair, dairy cows, and goat production. They introduced transboundary breeds such as Angora, Anglo Nubian, and Toggenburg goats, as well as Jersey and Holstein dairy cows. During the end of the 1990s, in response to local demands, the provincial government started providing economic support for research and development projects (R&D). Several programs received funding from the provincial state, with the aim of improving commercialization opportunities. Protective Denomination of Origin (PDO) seal for Creole Chivito Neuquino meat (López Raggi et al., 2010), and a market for combed Cashmere arose as a way to optimize local income and achieve fairer trade opportunities.

This sequence of development strategies led to a controversy at the scientific vertex about the modes of production for the region. One group set out with the bottom-up ideas to recognize the adaptability and resistance of local breeds and improve them with the active participation of the rural livelihood subsistence and niche marketing (Pérez Centeno, 2001; López Raggi et al., 2010). INTA through researchers and local and provincial extension services, focused on endogenous development. This group developed a formal on site scientific/technological knowledge. Later research concerned the characterization of the local Creole Neuquen Goat breed, which included health reproduction and traditional system. The growing number of publications (Robles et al., 1999; Lanari, 2004; Perez Centeno, 2007; Zimerman et al., 2007; Cueto, 2008; Maurino et al., 2008; López Raggi et al., 2010; Easdale et al., 2016) proves this.

Regarding controversies in the scientific vertex: other groups promoted another strategy for cashmere development The CONICET and Universidad de Cordoba researchers aimed at maximizing raw fiber production. They promoted electric shearing for the international brokers as opposed to combing Cashmere and elaborating goods locally (Frank et al., 2018).

The rural livelihood vertex identifies themselves as "crianceros." Transhumance is adapted to mountainous environments and adverse climatic conditions marked by seasonality. Additionally, herd movements allow an efficient territorial occupation and use of resources (Easdale and Aguiar, 2018). A social network strongly rooted in traditions, where members carry out diverse functions, sustains the system. The "castronerias" are an example of the social construction of these networks. Typical practice is to separate bucks from the does during the off-season to avoid winter calving and to ease the movements of the herds. Buck Keepers gather bucks from different owners and herds, generally in inaccessible places, mostly on public land. This practice is a key component of the annual production cycle, allowing synchronization of mating through "bucks effect" when males and does come together, and therefore strict seasonality. The Law (Provincial Law about Land Use N° 682) considers them illegal since it states that "crianceros" may run only their own stock on public land (Lanari, 2004; Lanari et al., 2007; Moronta et al., 2017). The transhumance pastoral system maintains several species, although the Neuquén Creole Goat is the one with the broadest representation and cultural importance.

The system possesses traditional knowledge that sustains its resilience and ability to adapt to the challenging environment of the southern Andes. "Crianceros" resisted attacks to their livelihoods, causing social resistance that still exists today (Easdale et al., 2019). However, development of formal scientific/technological knowledge caused changes in the way that the government vertex (laws, resolutions, subsidies, etc.) valued this system. The "Crianceros" have also changed. They proudly manifest and perceive themselves as such throughout the endogenous development of PDO (Pérez Centeno et al., 2007).

Several steps were undertaken to develop innovative products. By the development of the PDO in 2010, the commercialization systems improved by providing a more structured access to market. The installation of a spinning mill in Chos Malal in 2013 helped to develop a small-scale local textile industry and handicrafts (Maurino, 2020). Environmental transformations, urbanization and cultural changes are drivers of change and threaten the sustainability of the system (Easdale and Domptail, 2014).

Community-based programs or Biocultural Protocols can offer a framework and a first step for *in situ* conservation projects for animal genetic resources, making clear that the ownership is with the communities, as well as community owned and driven processes (FAO, 2007; Swiderska et al., 2012; Haile et al., 2020). This transhumance system has a close connection between communities and their Creole goat breed and has shown adaptations to environmental changes. To generate socioeconomic benefits in a future scenario, community-based programs should focus on genetics, grazing, legal instruments, and locally developed products using appropriate biocultural protocols. Tensions within the scientific vertex evolve to conflicts when advocating for different production systems (Easdale and Aguiar, 2018), thereby challenging the evolution of new products in the system. Biocultural protocols may help find pathways to get around environmental transformations, urbanization and cultural changes are drivers of change and threaten the sustainability of the system.

Wool Sheep and Guanacos in the Patagonian Province of Santa Cruz

Desertification represents a worldwide problem as reflected in the UN-Convention to combat Desertification. Defined as "land degradation in arid, semi-arid and dry sub-humid areas resulting from various elements, including climatic variations and human activities. The cause of this problem is a complex interaction between physical, biological, political, social, cultural, and economic factors (UNCCD, Article 1, 1994). These complex interactions can be seen in Santa Cruz. The historical production system was wool from Merino and Corriedale breeds, and more recently mutton on private lands. The three vertices analyzed here are aware of overgrazing problems caused by this monoculture production system.

To analyze this case study, the target will be on the National Law N° 25.422/01 for "The recovery of sheep husbandry in Patagonia." It is likewise necessary to look into the Provincial Law 3039/08 (subordinate to National Law N° 22421) that established the Provincial Program of Sustainable Management of Guanaco. The enforcement authority for these laws is the Consejo Agrario Provincial of Santa Cruz (CAP).

These two laws, National Law N° 25.422/01 and Provincial Law 3039/08 (subordinate to National Law N° 22421), are legal instruments that provide an opportunity to observe controversies and tensions in regional development policies as they are under different Ministeries, the MAGyP and MADS, respectively. Throughout the drafting of these instruments, actors from the three vertices mobilized their resources of power, within the rural livelihood unions and individually. These unions and individuals arranged meetings with the MADS and MAGyP authorities, as well as CAP, in a power struggle between national and provincial jurisdictions. Both instruments initially aimed to: (i) replace national enforcement authority by a collegiate body that includes provincial and rural livelihood representatives; (ii) access to funds from Law 25.422/01 limited to sheep producers.

INTA is responsible for providing research to Law 25244 and Law 224221. MAGyP authority makes decisions based on the research results of INTA and CAP. However, MADS makes management decisions mainly based on the opinions of CONICET researchers.

Scientists of this controversial space share a common ground about the importance of conservation of grasslands. Both assume a possibility that stocking rates (domestic and native herbivores) can be managed around some form of forage equilibrium. They also assume grazing of wild and domestic herbivores is additive and that the species compete for the forage. The focus of the controversy lies around where this equilibrium should be in relation to stocking rates (Marino and Rodriguez, 2018; Oliva et al., 2019; Marino et al., 2020).

The internal common ground of INTA researchers is the belief that natural resources need to be actively managed to produce marketable assets for rural livelihoods and urban society. The CONICET believe wild herbivores should occupy grasslands without domestic animals, because they believe that livestock keepers producers always overstock, resulting in land degradation. They advocate for land sparing because grazing management affects guanaco populations and considers tourism as an alternative revenue source for the rural livelihoods profits (Nabte et al., 2013; Marino and Rodríguez, 2018).

The most abundant population of guanacos is in continental Patagonia. A survey in 2001 estimated 220,000 for the province of Santa Cruz. In 2013 the number of guanacos were estimated to be 1,350,000, representing 65% of the Patagonian population and an annual growth rate between 10 and 15% (Amaya et al., 2001; Manero et al., 2013; Bay Gavuzzo et al., 2015; Travaini et al., 2015). This rebound of guanacos population drew public attention and led to further controversy among the three vertices. Santa Cruz evolved into the classic arena of conservation—production conflict as rural livelihoods use arguments of this controversy to claim economic losses.

The rural livelihoods endured three catastrophic events that followed each other in the mid-nineties. The environment was adversely affected by convergent drivers in the 1990s. These were a sequence of prolonged periods of drought aggravating desertification, president Menem's administration and economic policy, and the eruption of the Hudson volcano in 1991 (Wilson et al., 2011; Andrade, 2012; Taraborrelli and Pena, 2017). The eruption produced 4.3 km3 volume of tephra deposits spreading ashes over 120,000 km2 (Scasso et al., 1994; Kratzmann et al., 2008, 2010). Following tephra fall, around 1 million domestic animals died of starvation and waterhole contamination with ashes producing dehydration, blindness, teeth erosion, and also human health problems (Wilson et al., 2011). This scenario caused de-stocking and abandonment of farms (Wilson et al., 2011; Andrade, 2012; Taraborrelli and Pena, 2017) and consequently should have alleviated grazing pressure.

In the aftermath of these events, the rural livelihoods through the Federation of Agricultural Institutions of Santa Cruz reported an increase of guanaco's population between 2004 and 2014, causing additional deterioration of grasslands (Andrade, 2002; Wilson et al., 2011; Taraborrelli and Pena, 2017). Leaders advocated the idea to cull guanacos for meat. This would help to balance the overgrazing problem and provide jobs and equity to rural livelihoods. However, this meant developing a novel product, with accompanying laws and rules.

Santa Cruz currently supports two strategies for obtaining novel products. Farmers advocate for culling guanacos for meat and a mixed management to compensate for diminished carrying capacity. Conservationists advocate for rewilding by land sparing. However, both need to solve issues around key monitoring activities of results. Culling guanacos needs a very transparent socioecological monitoring system. Provincial authorities enacted a law that temporarily stops new protected natural areas. They demand an updated inventory of the agricultural and non-agricultural establishments, properties, and public and private lands in the rural area of the province of Santa Cruz.

DISCUSSION AND CONCLUSIONS

Sustainable use controversies of rural areas are complex because they exist in interdisciplinary and inter-institutional environments. They are about decision-making and access needs to lobbying resources. The three case studies discussed herein have similarities and differences in their focus and common grounds of the controversial spaces (**Table 1**). They create networks of relationships and bonds leading to intermittent results. Simultaneously, differences in common ground evolve causing conflicts. Questions of for whom and who should perform research and decision-making in communities: the rural livelihoods? The state? Researchers? Each case study has particularities and styles.

Researchers have a common ground, with the end goal of the sustainable use of vicugna and guanacos. Additionally, for the Creole goat case study, the common ground is that this breed can produce Cashmere fine fibers. However, in the three case studies common ground differs among research groups. The precautionary principle, which types of products, and how they are obtained, represent the pathways to conflicts because they contain political beliefs and networks forging opposing coalitions.

Political beliefs and traditions, as well as individual educational experiences define how the extension of experiences are approached. Top down or bottom-up experiences hold distinct epistemological and research consequences and they affect rural livelihoods in various ways. The processes of the three cases have been mixed, as they dynamically change over time. For the three rural livelihoods, meaningful regulations should be endogenous social constructions. The government and the opposed groups of the science vertices recognize the right of indigenous communities to their genetic resources in accordance to the Nagoya Treaty. In the Puna case, this appears to contradict the precautionary principle and the fauna legislation that grants the rights to the provinces. The controversy over genetic bottlenecks in both wild camelid populations faded as numbers increased and some data were available.

Different PAR methodologies in the three case studies provide opportunities to promote endogenous processes allowing a range of appropriate procedures. They could be practiced to surface the issues that seem to provide common ground but are not, thereby helping respect cultural values among and between stakeholders. Regardless of the method employed, it must produce a virtuous cycle that entails reflection, learning, and adaptation, which is facilitated by a communication strategy involving the data obtained throughout the process. This can increase transparency and enhances a common ground of trust in the social construction process.

Several programs received funds from the provincial state. The aim was to improve commercialization opportunities by creating a Protected Denomination of Origin (PDO) seal for meat from Creole Chivito Neuquino (López Raggi et al., 2010). Small deharing and spinning mills to develop a market for vicugna, Cashmere and guanaco's fiber are presently available near the production areas. The two vicugna groups have achieved little progress on marketing raw or different stages of processed products. Only one slaughter-house is permitted to collect and export the culled guanacos meat. As the program is recent, little data exist about how rural livelihoods market the product and culling effect. Access to the markets is still a problem to the rural livelihoods for the three case studies as they are remote from commercial centers, transportation, and communication (**Figure 1**).

Space and time scales are different for each vertex. The rural livelihood timescale occupies three generations and a variable distance between its animals and the nearest town. Researcher's timescales depend on project's lifespan or their interest in their professional life (i.e., three to maximum 40 years). Their landscapes run between their institution, the field of research, and global contacts. Theoretical governments' turnover rate occurs every 4 years, therefore their timescale is short and survival depends on power of coalitions. Their landscape is contained in the province and connections to the central government. Consequently, networks and identities may change over these different life courses. Similarly, life histories of products and marketing strategies change. The outcomes are tensions and disputes that challenge the ability to attain the sustainability goals initially set by each group. Moments of success are followed by moments of destruction. These depend on the type of alliances achieved and on transforming the processes in the hands of few actors or leaders. Amplifying responsibilities for community processes appropriated by as many players as possible, may represent a future strategy of sustainability.

Following Nudler's (2004), Voß and Bornemann (2011), Hill et al. (2013) controversial spaces may offer leverage points by reframing the controversies and adding value to negative results. These experiences were conspicuously absent from the literature. A long-term joint monitoring of these experiences would also help to leverage controversy to enrich future sustainability. As is common with wicked problems, there is no unique answer to the three case studies analyzed here and this manuscript has created more questions than solutions. However, the case studies do have overlapping solutions. For example, long-term multispecies grazing opportunities are available for the three case studies. Ultimately, it depends on how actors in the vertices can acquire flexibility in their common ground to face catastrophic events.

Public policies have evolved into elements of struggle for all engaged actors. Policies have altered the structure and the way of approaching programs offered to rural livelihoods in the provinces. In the three case studies, participants began making their requests for legal status of land tenure, use of territorial spaces, and appropriate technologies, which translated into strengthening the organization of livelihoods. However, cultural diversity and cohesion also suffer erosion in the adaptation process (Bendini et al., 2004; Walter et al., 2007; Borghini, 2010).

The scientific and technical teams fulfilled a role that began to drive the different sector interests according to their visions and epistemologies, which also evolve over time. The dynamics of the players in these state policies allows us to perceive the state as an actor that is neither monolithic nor homogeneous. Multidirectional and often contradictory thought processes are in competition for resources between institutions and for the support from society, at a given historical moment.

A difficulty to assess progress of programs is the absence of shared quality information and data among all actors. This lack of trust among actors delays learning and adjusting as indicated by the continuous evaluation of outcomes. There is a need for a system that shares results within government, the science community, and rural livelihoods, containing and acknowledging controversies (bottom up and base down, etc.). The system included in the construction and development of the programs should help to build trust and help learn and adapt according to ongoing results.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements. Ethical review and approval was not required for the animal study because We are using published data and no type of experiment was conducted.

AUTHOR CONTRIBUTIONS

JT conceived the idea. ML provided information on the cases. EM provided information and analysis of the legal aspects of the cases. JT and ML wrote and revised the paper.

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SUPPLEMENTARY MATERIAL

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The Role of Community Cooperative Institutions in Building Rural–Urban Linkages Under Urbanization of Pastoral Regions in China

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In contrast to agricultural settings, the process of urbanization in the pastoral regions of China are largely driven by long-term influences of ecological conservation and the provision of social services. Consequently, many of the herders who have migrated into nearby secondary urban centers depend on resources from pastoral regions to support their livelihoods, forming complex patterns of rural–urban linkages. While current literature has discussed the processes of herder out-migration and their implications on rural and urban livelihood development, few studies have examined the linkages between the herders living in the pastoral regions and those who have out-migrated to urban regions and their importance in rural livelihood transformation. Based on past studies, we argue that, in a changing pastoral social–ecological system, herders living in both rural and urban regions depend on each other to support their livelihoods through three types of mobility: (1) livestock mobility, (2) herder mobility, and (3) resource mobility. However, what innovative institutions in rangeland resource management and herder economic cooperation can do to help maintain these three types of mobility to sustain rural livelihood development, becomes a critical challenge. Innovative community cooperative institutions developed by pastoral communities from the Tibetan Plateau and Inner Mongolia may be able to offer new perspective and insight on how to better maintain rural–urban linkages in the processes of urbanization in pastoral regions. In this current study will present the two cases of innovative institutions and the roles they play in facilitating the three types of mobility to address livelihood challenges. While current studies recommend an increase of government subsidies, provision of vocational training, and social insurance that help herders better adapt to urban livelihood, we argue that rangeland management and community economic cooperation in innovative institutions are needed to facilitate the mobility of livestock, resources, and the herder population, and maybe only then the livelihood challenges that migrated herders are facing will be addressed effectively.

Keywords: urbanization, rangeland institution, herder cooperative, grazing quota system, pastoral region

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INTRODUCTION

Rangelands cover 400 million ha, accounting for 41.7% of China's total territory, among which 3/4 of the rangelands are distributed mainly in China's west regions (MOA, 2014). These regions are mostly located in arid and semi-arid regions and alpine steppes with either a long cold season or a dry hot season (Sheehy et al., 2006; Li and Zhang, 2009). These are some of the world's poorest and most marginalized areas but also some of the most innovative and enterprising, responding to environmental, market, and governance uncertainties in ways that can offer vital insights elsewhere (Scoones et al., 2020). In the contemporary context of social–ecological changes, pastoral communities in China are being rapidly integrated into multilevel networks characterized by deep uncertainties, including climate variability and environmental change, a volatile market and financial systems, the increasing mobility of the population that has resulted in the reconfiguration of rural socio-economic structures, resource use and access rights, and institutional arrangements (Gongbuzeren et al., 2018; Nori and Scoones, 2019; Qi and Li, 2021). Urbanization of pastoral regions is one of these great socio-economic transformations that has increased the movement of herder populations between rural and urban areas and has restructured rural livelihoods (Bao and Shi, 2020).

In contrast to urbanization in the agricultural regions of China, where population out-migration are voluntary movements induced by marketization and economic opportunities (Jin and Li, 2019), the urbanization processes in pastoral regions are driven by long-term interactive influences of multiple policies including rangeland ecological conservation policies (caoyuan shengtai jianshe), the rural school consolidation policy (chedian Bingxiao), rangeland institutional reforms (caochang zhidu gaige), and rural poverty alleviation programs (tuoping gongjian zhengce) (Washul, 2018; Bao and Shi, 2020). In particular, ecological conservation programs including "retired grazing to restore grassland" (tuimu huancao) and "ecological migration program (Shengtai Yiming)" are among the major strategies that have encouraged pastoral households to resettle in townships and county seats (Ptackova, 2011; Du, 2014; Jiumaocuo and Wang, 2016). Scholars also discovered that the Rural School Consolidation Policy, which was launched nationally in 2001 and implemented in various Tibetan areas at later dates, has spurred the closing of the majority of village schools, and rural children are now forced to live in boarding schools in distant townships or county seats, starting from an early age (Bum, 2018; Yeh and Makely, 2019). This policy further accelerated the out-migration of many rural herders to resettle in adjacent sub-urban regions. Herder out-migration in pastoral regions has therefore been driven by top-down policy interventions, integration of rural pastoral regions into marketization, and voluntary herder movements (Wang and Xiu, 2014; Jin and Li, 2019). In this process, two major patterns of out-migration have emerged to form complex rural–urban linkages. First, the whole pastoral family resettles in urban areas, though many of them cannot find viable income sources in urban regions, so they continue to rely on resources from pastoral regions, including the collection of caterpillar fungus and livestock production, to support their livelihoods in the urban area. Second, family members live separately in two regions, where elders accompany their children to live in the urban areas while young people from the family stay in the pastoral regions to maintain their livestock production and to support their livelihoods. Therefore, unlike agricultural regions where labor out-migration tends to explore alternative income sources to support their rural home, out-migrated herders depend on rural rangeland resources to support their livelihood and expenditures in urban regions.

As urbanization processes in pastoral regions have been accelerated with complex patterns of herder population mobility, there has been an emerging number of studies in recent years, focusing on the impacts of urbanization on the herder population and their livelihoods. Using "urbanization in pastoral regions" as a keyword to do a search in CNKI, we have discovered that over 143 journal papers that were written in the Chinese language were published between 1999 and 2020 that focus on the urbanization of pastoral regions. These journal papers focus mainly on three major themes about urbanization in the pastoral regions. First, many of the past studies focus on the pull and push factors of herder out-migration (Dai et al., 2009; Jin and Li, 2019). These studies argue that policy-driven out-migration such as ecological migration programs and rural school consolidation policies are the push factors for involuntary migration, which cover the majority of rural herder population movements (Fan et al., 2015). Others argue that the young generation is showing a high level of unwillingness to continue pastoralism livelihood, which is a major push factor, and the desire to find stable jobs is a pull factor for voluntary migration (Dai et al., 2009; Li, 2012). However, studies also discovered some patterns of herders moving back to pastoral regions after a few years of living in the urban and suburban regions as they could not find stable income sources (Du, 2014; Wang and Xiu, 2014). Second, with a high level of herder mobility, studies focus on herders' ability to adapt to urban socio-economic structures and their livelihood development challenges. Regarding this, even though some studies argue that herder resettlement improved access to better education and healthcare, with more opportunities to diversify their income (Liu and Wang, 2008), many studies gradually discovered a variety of challenges affecting their livelihood, with increased wealth differentiation (Li, 2012, 2013; Fan et al., 2015; Gongbuzeren et al., 2015; Zhang, 2020). In many cases, studies discovered that herders have poor technical skills and low literacy levels which limit their ability to find viable employment, and even those who are able to find jobs usually have low-paying ones (Zhu, 2018; Jin and Li, 2019). In addition, there have been all types of discrimination toward the migrated herders from the original urban residents that further exacerbate out-migrated herders' ability to adapt to urban livelihood (Li, 2012). Consequently, studies argue that out-migrated herders have encountered both livelihood poverty and the challenges of social marginalization and cultural isolation. Many of those out-migrated families, therefore, have relied on government subsidies as their main source of livelihood. To address these issues, many studies recommend increasing government subsidies, provision of social insurances including medical insurances, and targeted vocational training that could help the migrated herders find better employment and income sources (Wang and Xiu, 2014). Third, there are also studies that argue that herders should not leave pastoral regions as livestock production and grazing activities are part of the pastoral social–ecological systems that not only sustain herder livelihoods but also protect rangeland ecosystems and biodiversity. In summary, these studies argue that policies should pay greater attention to innovative strategies that could provide social services and develop markets for livestock production while keeping herders in the pastoral regions rather than forcing them to move to urban regions (Gongbuzeren et al., 2015).

The number of studies focusing on the urbanization of pastoral regions has increased in recent years and has provided empirical information and understanding on the pull–push factors of herder out-migration and their livelihood challenges. However, these studies focus either on migrated herder populations and their livelihoods or on those herders who remained in the pastoral regions and their socio-economic and ecological issues, while many failed to capture the coupled feedback and linkages between the herders living in pastoral regions and those who are being resettled in urban regions. Studies argue that rural livelihood transformation under urbanization is a long-term process where herders living in both urban and rural regions need to depend on complex patterns of linkages between rural and urban regions to access markets and rangeland resources that sustain their livelihood (Huntsinger et al., 2010; Eriksson, 2011; Du, 2014; Fan et al., 2015; Zhang, 2020). We therefore argue that we need to frame the issues of urbanization in the pastoral regions from a perspective of seeing the rural and urban regions as a coupled system. Based on the social–ecological features of pastoral regions, we have developed three conceptual mobility types that we believe could maintain rural–urban linkages to address herder livelihood changes under an accelerated process of urbanization. These three types of mobilities include livestock mobility, herder mobility, and resource mobility.

First, livestock mobility is a major characteristic of traditional pastoral systems globally, a production and coping strategy that facilitates greater levels of livestock production, use of shared labor, escape from localized drought or cold, access to landscape heterogeneity, and use of widely dispersed water sources (Behnke et al., 1993; Li and Huntsinger, 2011; Kratli, 2019). However, when the Rangeland Household Contract System was implemented in the late 1990s, allocated pastures were fenced, land use as well as tenure became fragmented, and the scale of herder movements was reduced (Li and Zhang, 2009; Gongbuzeren et al., 2015). The larger spatiotemporal scales of herd mobility that were formerly possible are no longer feasible (Gongbuzeren, 2019). Community relationships based on reciprocity, which supported shared pasture use and labor, are also fragmented as households focus on earning a livelihood from individual pastures (Li and Huntsinger, 2011). This has created an institutional controversy and dilemma for both groups of herders living in pastoral regions and urban areas. On one hand, individualized tenure has reduced their ability to access seasonal pastures for herders who stay in the pastoral regions and has increased livestock production costs. Many of those out-migrated herders who still keep livestock in the pastoral regions face similar challenges. Therefore, recent scholars and policymakers also recommend institutional changes that encourage the re-aggregation of individual rangeland resources and restoration of community collective use of rangelands (State Council, 2016; Li et al., 2018; Qi and Li, 2021). However, on the other hand, studies also discovered that the increased level of herder out-migration increased conflicting values and competing priorities over the use and management of rangeland resources within pastoral communities (Kamoto et al., 2013; Gongbuzeren et al., 2018). Rural communities who have collectively used their natural resource may now find themselves with individuals, especially out-migrated herders, who do not have livestock, demanding more privatized and clarified property rights to protect individual benefits and opportunities (Gongbuzeren, 2019). Therefore, how to restore or maintain community collective use of rangelands and seasonal livestock mobility while protecting individual tenure security and benefits becomes a critical challenge.

Second, the improved infrastructures in China's rural regions and the increasing commodification and extension of capitalist systems of production in rural regions have diversified the use of and the economic values of the rangelands (Thornton and Manasfi, 2010; Cleaver, 2012; Chaudhury et al., 2017), increasing herder mobility and resource mobility between rural and urban regions. On the one hand, under current socio-economic changes, rangelands not only support livestock production but they also provide resources for the development of ecotourism, the collection of lucrative medicinal herbs such as caterpillar fungus, and the rental of grazing lands to earn a fee (Gongbuzeren et al., 2018). In particular, the development of the rural tourism industry in the pastoral regions of the Tibetan Plateau in the last decade has increased with a massive number of tourists visiting rural pastoral communities, creating all types of consumer markets for rural livestock products and cultural artifacts. Therefore, migrated herders continuously move between urban and rural regions to access resources from the rangeland to support their livelihoods while they explore other livelihood options in urban regions (Jin and Li, 2019; Bao and Shi, 2020; Zhang, 2020). On the other hand, the number of cultural industries and businesses such as Tibetan restaurants and cultural performance centers have also increased in urban and suburban regions. Members of rural pastoral families are gradually moving into urban regions to engage with small-scale business opportunities or get temporary employment in these culturally related business entities. Therefore, even though livestock production and other resources from rangelands are the main sources of livelihood for herders who stay in pastoral regions, they also try to participate in current markets to explore other income opportunities. Given this, both groups of herders living in rural and urban regions constantly move between rural and urban regions to access resources, forming complex patterns of herder and resource mobility.

We argue that livestock mobility, herder mobility, and resource mobility are key features of rural–urban linkages in the process of urbanization in pastoral regions to address livelihood development challenges for herders living in rural and urban regions. However, maintaining all three types of mobilities creates critical challenges for rangeland management institutions and tenure regimes, as it requires institutions operating across multiple scales to rebuild cooperation and collective action among the herders. First, at the household scale, a clarified individual right is needed to protect individual benefits and use of rangeland resources for both groups of herders. Studies have raised critiques of traditional community-based natural resource management institutions to have over-focused on community shared goals and common property rights while leading to the differentiated distribution of resources and power among individuals, which favor the powerful and disadvantage the marginal (Nightingale, 2011; Ojia et al., 2016). Therefore, clarification of rights at household scales to achieve equal distribution of rangeland resources and to facilitate resource mobility becomes fundamental (Gongbuzeren et al., 2018). Second, extensive research studies argue that community common property rights and management of rangelands are critical for maintaining seasonal livestock mobility with flexible access to rangeland resources to better adapt to ecological changes (Miehe et al., 2009; Gongbuzeren, 2019). In addition, studies also discovered that lucrative medicinal herbs such as caterpillar fungus only grow in certain regions of the community rangelands (Zhang, 2020). Restoration of common community property, therefore, will not only restore livestock mobility but will also facilitate resource mobility through guaranteed equal access to caterpillar fungus for all herders. Third, pastoralists are increasingly commercializing, often through local market connections and sometimes to lucrative international and regional markets (Scoones et al., 2020), and as a driver of social differentiation within pastoral populations, access to markets is key (Catley and Aklilu, 2013). However, some pastoralists are able to step up toward more commercial pastoral production systems, capitalizing on growing markets in livestock production, while others are simply hanging on, combing limited pastoral production with other activities, leading to "moving up, moving out" scenarios with increased wealth differentiation among herders living in rural and urban regions (Aklilu and Catley, 2010; Catley et al., 2013; Zhu, 2018). Therefore, studies encourage the development of institutions and a moral economy that is focused on rebuilding community cooperative economic entities with the sharing and redistribution of resources within pastoral communities to ensure that all herders living in a rural region and those being resettled in urban areas have access to, and gain benefits from markets (Zhu, 2018; Scoones et al., 2020). Finally, in rebuilding community cooperative economic entities, rural herders may be able to access resources and support from governments, civil societies, and markets at the regional level.

The need for institutional diversity and innovation are essential in maintaining livestock mobility, herder mobility, and resource mobility in pastoral rural–urban linkages. In 2016, after 30 years of implementing the Rangeland Household Contract Policy (RHCP), the Chinese government initiated "Suggestions on Improvement of Ownership Rights, Contractual Rights, and Use Rights in Rural Land" (sanquan fenzhi) to divide the existing two rights, ownership and contractual use rights, into three rights: ownership, non-tradable contractual rights, and tradable management rights (State Council, 2016). It has been argued that such land tenure reform can provide the institutional flexibility to re-aggregate individual rangeland resources and to rebuild cooperative business entities. However, in actual practice, studies have discovered that this policy has been mainly practiced through a rangeland rental system between individual households without being able to restore community cooperation (Lai and Li, 2012; Li et al., 2018; Gongbuzeren et al., 2020). Even though the land rental system generates income for some of the migrated herders, it does not effectively address the three types of mobilities to maintain rural–urban linkages in pastoral regions. Therefore, knowing what innovative institutions could help rural herders to rebuild community cooperation while protecting individual rights and benefits to maintain rural–urban linkages becomes a critical challenge.

We believe that some of the innovative rangeland institutions that are self-organized by rural pastoral communities in the pastoral regions of China may be able to offer critical insights and contributions to the issues discussed. According to our fieldwork, we believe that these newly emerged institutions can be categorized into two major featured groups. First, even though the government has promoted the rangeland household contract policy, in practice, however, many communities maintained collective management and use of rangelands, and based on community organization, herders self-organized a tradable grazing quota system to protect individual rights and benefits in recent years. Second, after the implementation of the rangeland household contract system with the building of wire fences to demarcate individual grazing boundaries, herders collaboratively decided to remove the fences and rebuilt community collective management of rangeland resources. At the same time, such a management system protected individual rights and benefits through the distribution of bundles of entitlements to resource and market access, such as entitlement to an equal share of investment stock in the community collective enterprises. In both groups, the pastoral communities have applied hybrids of informal customary rules and formal market-based institutions to restore community cooperation over the management of rangeland resources and participation in marketization, while redefining the networks and distribution of benefits and rights among individual herders. We believe that these self-reorganized institutional innovations provide an interesting perspective on how pastoral communities have evolved and changed through processes of urbanization to rebuild institutions that could maintain or restore livestock mobility, herder mobility, and resource mobility between herders living in rural regions and those being out-migrated in urban regions. We have presented two case studies from our past research to further illustrate how pastoral communities in China have developed innovative rangeland institutions and show the perspectives these cases present in advancing our understanding of the roles of community cooperative institutions in building rural–urban linkages.

CASE 1: COMMUNITY-BASED HERDER COOPERATIVE IN INNER MONGOLIA

This section discusses a case of a community-based herder cooperative from the pastoral regions of Inner Mongolia. Inner Mongolia is one of the first pastoral regions that have strictly implemented the Rangeland Household Contract Policy, though after years of practicing this policy, innovative rangeland management institutions are emerging. This case of a herder cooperative is one such innovative community-based institution that re-aggregated individualized grazing areas to restore the collective community use of rangelands.

New Baerhu Right Banner is located in the northeast of Inner Mongolia, adjacent to the borders of Russia and Mongolia. The case study site, H Gacha (a village in Inner Mongolia), is in the northern part of the Banner, west of Hulun Lake. The community rangeland is a meadow steppe, with an average annual precipitation of around 189 mm. In 2012, the village had a total of 44 households with 147 people; all of them are Mongolian. Livestock production is the main source of income. Herders mainly raised sheep, with a few goats, cattle, and horses.

In 1996, the village contracted their rangelands into individual households, with wire fences built to demarcate boundaries between individual grazing areas. However, after nearly 14 years of practicing this policy, herders in this village went through a variety of challenges (Lai, 2012). First, the high frequency of weather disasters, especially drought, led to high livestock mortality and pushed many families in the village to give up livestock production completely. By 2009, over half of the community households did not have livestock. Many of them either worked for other pastoral families to herd their livestock or moved out to adjacent urban towns to find alternative income sources. According to an interview from the studies of Lai (2012), many of these herders who had to give up livestock production earned a minimum income to support their livelihoods. Second, those pastoral households who do not have livestock, rented out their grazing areas to herders outside the village to earn an income, though this led to an increase in the overall grazing pressure in the community rangelands. Consequently, the community rangeland conditions have deteriorated, and many of the pastoral households had to spend more to purchase fodder and feed to supplement livestock foraging needs. Given these issues, the community decided to establish a herder cooperative, a community collective business entity in which all 44 households from the village participated.

The community cooperative applied several strategies to restore the community's collective use of rangelands and collective business entities (Lai, 2012). First, herders in the village can use either livestock or their contracted individual grazing areas as starting capital to participate in the cooperative, and all herders in the village are entitled to a stock share from the cooperative business. Second, as many individual grazing areas become part of the cooperative's capital and the cooperative collectively rented in the individual grazing areas from the families who migrated to live in urban regions, they collectively decided to remove all the wire fences that demarcated individual grazing boundaries and restored the community's collective use of rangelands with seasonal livestock mobility at the community scale. Third, the cooperative consists of four departments, including mechanics for harvesting fodder, a livestock production department, a marketing department, and a tourism department. The cooperative reinforced community management and organizations to regulate their rangeland management systems including prohibiting herders from renting out their rangelands to outsiders.

According to a herder interview (Lai, 2012), this management system generated several key benefits to the local herders. From an ecological aspect, as the cooperative collectively use their rangelands with regulations of no renting of grazing areas to outsiders, the spatial distance of livestock movement has increased, different grazing parcels get a chance to rest and recover, and the overall grazing pressures have been reduced. The remote sensing data from Lai and Li (2012) compared the normalized difference vegetation index (NDVI) values of five paired sites, with each of the pairs including a pasture that has never been leased out (self-use) and its neighboring pasture which used to be self-used (blue area) and then leased out (gray area) and currently under cooperative management (yellow area) pastures. Their study results demonstrate that the level of NDVI in the leased rangeland is lower than when they were self-used, indicating lower vegetation productivity when the rangelands are leased out. When the rangelands are re-aggregated and used collectively under the cooperative management, there are trends of increased NDVI levels. Therefore, differing from the rangeland transfer system that leased out rangelands to different people in many short terms, the rangeland re-aggregation and restoration of seasonal mobility under herder cooperatives help to reduce the overall grazing pressures on individual grazing parcels through the collective use of the rented-in rangelands so that it may be able to prevent and even restore rangeland degradation in the long-term.

Lai's research (2012) demonstrates that the establishment of the herder cooperative helped to improve herder livelihood while protecting their individual benefit and rights. First, based on the number of individual grazing areas or livestock numbers that they have invested in the cooperative, each pastoral household, whether already moved out into urban areas or continuously living in the pastoral regions, is entitled to receiving a share of benefit distribution at the end of the year, based on the cooperative net benefits and income. In addition, the cooperative hired many of the herders who did not have livestock and worked in the urban areas, who decided to come back and work in the cooperative as a long-term employment. Second, the cooperative helped individuals to reduce costs for purchasing fodder and saving livestock production labor under the cooperative management. The average expenditures on fodder purchases accounted for 33–43% of total livestock production costs in Inner Mongolia after the implementation of the RHCP. The cooperative's members are able to purchase the fodder at a price of 21 yuan/bale in 2011, which is lower than the regular market price of 25–30 yuan/bale. Similarly, the cooperative collectively herd all of the members' sheep. In summer, they hire six shepherds, while in winter they only need four. The shepherd's wage is 2,000 yuan/month under the cooperative, and all members only need to support the wage of six shepherds, whereas in the pre-cooperative era, each family may have needed to hire a shepherd. Therefore, each household is only spending 1/3 of the previous costs on shepherd wages.

According to Lai's (2012) interview, some of the herders stated: "After the establishment of the herder cooperative, we do not need to rent out rangelands to others and invested our lands in the cooperative. In this way, we are still earning income from our grazing lands as we did before under the rangeland rental system, but with better care and higher income." As this herder has stated, we believe that this herder cooperative management system demonstrates innovative community-based institutions that stimulate the improvement of livestock production, herder livelihood, and rangeland ecosystem while protecting the individual rights and benefits of herders living in pastoral regions or those who choose to migrate to urban regions.

CASE 2: COMMUNITY-BASED GRAZING QUOTA SYSTEM IN THE TIBETAN PLATEAU

Our research in the pastoral regions of the Tibetan Plateau discovered that (Gongbuzeren et al., 2016, 2018), while some pastoral communities maintain common community use of rangelands based on their customary institutions, they began to pay attention to the needs of individual households in the rangeland management system (Gongbuzeren et al., 2016). Along with the promotion of the rangeland transfer system that opened up new markets for the rangeland rental system, rangelands are not limited to the resources for livestock production but are used for resources that can be traded for generating income. Following this fundamental change, many herders in the community's collective use of rangelands anticipate a certain level of individualized property rights to protect individual tenure security and benefits. Particularly, those families who do not have livestock and migrated into urban areas strongly demanded clarified property rights so that they can earn income from their individual pastures. However, many of the pastoral communities wanted to maintain collective community use of rangelands to facilitate seasonal livestock mobility at the same time. Given this, recent studies discovered that innovative rangeland management institutions are emerging in the pastoral regions of the Tibetan Plateau, including a group collective use of rangelands (Cao et al., 2013; Gongbuzeren et al., 2020), a community-based grazing quota system (Gongbuzeren et al., 2018), and herder cooperative management (Wang et al., 2016). The community-based grazing quota system is a commonly applied innovative institutions to manage rangeland resources.

In the case of the community-based grazing quota system, C Village, from the pastoral regions of the Tibetan Plateau is located in Guinan County of Qinghai Province. The village has a total of 431 households, with a population of 2,000 Tibetan pastoralists (Gongbuzeren et al., 2016). Livestock production is the main source of household income. Historically, common property rights for range management supported the collective use of rangelands, with seasonal mobility of livestock as the main grazing strategy. Similar to other pastoral communities of the Tibetan Plateau, the C Village was under the commune system from the 1950s to the early 1980s. In 1982, the government initiated the Household Production Responsibility System, privatizing livestock to individual households. Rangelands were left to collective use by the village until the early 1990s, when the government began promoting the Rangeland Household Contract Policy, allocating specific land parcels to households. In C Village, each household received a paper contract from the local government showing the area and location of the rangeland where the household had individual user rights, but the villagers divided up only their winter pasture and continued community collective use of their spring/fall and summer pastures. In 2009, C Village collectively decided to develop a grazing quota system that allowed them to continue the common use of summer and spring/fall pastures and maintain four seasonal livestock migrations each year, while it clarified the individual grazing quota system.

The community-based grazing quota tends to clarify individual grazing quota based on the total livestock numbers that the herders believe their community rangelands can support and sets a quota for livestock numbers for each village member. The individual quota changes every year based on the quality of their grazing area. Quotas can be transferred from one villager to another *via* a fee system run by the community for those with extra or too few livestock to use their quotas. They charge a fee to households whose livestock numbers exceed their grazing quota and distribute the money as compensation to households using less than the quota so that households without enough livestock still make an income. The community-based grazing quota system clarifies tradeable rights to a share in the grazing quota at the individual household scale so that herding households can maintain mobility, community management practices, and shared labor at the community scale.

According to the studies of Gongbuzeren et al. (2016), this management system generated several benefits for the local herders. First, based on the implementation of the rangeland household contract on paper, the community-based grazing quota system clarified the individual grazing quota that protected individual rights and benefits from rangeland resources. Consequently, many of the poor families who do not have livestock and migrated to urban areas could obtain compensation from rich families who have higher livestock numbers. Second, while the grazing quota system is clarified to an individual household, the community collectively manages and uses rangeland resources for seasonal livestock mobility. This helps the herders control livestock production costs and improve livestock production return. Third, the grazing quota system helps herders control the livestock numbers while not undermining livestock production efficiency so that rangeland degradation is not observed (Gongbuzeren, 2019).

CONCLUSIONS

Livelihood transformation under urbanization in the pastoral regions has been a long-term process, where out-migrated herders face many critical livelihood challenges and have to depend on resources from pastoral regions to support their livelihoods, forming complex patterns of linkages between rural and urban regions. In addressing these challenges, we proposed an operational framework in this paper that frames the linkages between herders living in pastoral regions and those living in urban regions within three types of mobilities, including livestock mobility, herder mobility, and resource mobility. However, how these three types of mobilities are maintained becomes a critical challenge for rangeland management institutions, as it requires institutions operating across multiple scales to rebuild cooperation and collective action between the herders living in rural pastoral regions and those living in urban areas. Government policies support the wide implementation of a rangeland transfer system based on further completion of the rangeland household contract policy, though our field research in the pastoral regions of Inner Mongolia and the Tibetan Plateau has discovered that rural communities have developed innovative rangeland management institutions that may provide more effective solutions to maintaining the three types of mobilities to address livelihood challenges in the process of urbanization.

We believe that the discussions of herder livelihood transformation in the process of urbanization and the innovative rangeland institutions in addressing livelihood challenges have some important implications and references to other pastoral regions who face similar challenges, and they require future studies with in-depth scrutiny.

First, this study proposed the assumption that, even though there is an increasing number of studies that have focused on the pull–push factors of herder out-migration and the livelihood challenges that out-migrated herders encounter, very few have focused on how to maintain the linkages between the herders living in rural and urban areas and if such linkages could be key in addressing the livelihood challenges that they face. Livelihood transformation under the urbanization of pastoral regions is a long-term process where herders living in both rural and urban regions need to continually depend on resources from both sides to support their livelihoods. Therefore, we argue that the three types of mobilities discussed in this paper are the key dimensions of rural–urban linkages in the pastoral regions through which herders living in both rural and urban regions can access resources and markets to address their livelihood challenges. This further indicates that discussing social–ecological issues under urbanization in pastoral regions requires a perspective of viewing the herders living in rural pastoral regions and those who live in urban regions as a coupled system, a perspective that has not received adequate attention in the current literature.

Second, we argue that, even though rural–urban linkages are critical, how to maintain them is challenging, especially for rangeland management institutions. In the process of urbanization, many of the out-migrated families demanded clarified property rights to increase their tenure security as well as so that they can rent out their individual grazing parcels to earn income. Therefore, many herders who maintained the collective use of rangelands start to self-organize a more individualized tenure regime. However, contracting rangeland to individuals restricts livestock mobility and the ability to adapt to ecological dynamics for herders living in rural regions. The herders who continue living in the pastoral areas prefer more flexible institutional arrangements that provide access to seasonal grazing. Given this, this paper argues that future studies on rangeland management institutions need to go beyond the traditional debates on whether rangelands should be privatized or managed under common property rights. Some studies already discovered the need for nested property rights and hybrid institutions operating at multiple scales to adapt to changing pastoral social–ecological systems (Gongbuzeren et al., 2018; Qi and Li, 2021), but more studies with empirical fieldwork are needed on rangeland institutional changes and innovations under urbanization.

Third, enabled by the influences of the rapid growth of urbanization and market-based economic development, many of the rural pastoral regions on the Tibetan Plateau are highly integrated with modern marketization. In addition to all the family out-migrations that have mostly occurred under ecological migration and rural education reform policy, there is also much voluntary migration of rural herders, especially young laborers who temporally move to urban areas to seek alternative income sources. Even though many studies focused on the patterns and trends of rural population movements and the pull–push factors behind these movements at provincial and country levels, very few studies have focused on population movements in pastoral regions. Therefore, more empirical and case-based studies are needed to assess the patterns of herder population movements and their impacts on rural pastoral development.

Fourth, urbanization and other rural development policies increased the linkages between rural pastoral regions and the regional or international markets, diversifying the uses and values of rangeland resources. While livestock production is still the main income source of rural herders, they also tend to engage with other rangeland economic activities such as tourism, collection of caterpillar fungus, handicraft sales, and secondary processes of livestock products such as milk liquor or yak milk ice cream. Therefore, both government policies and many research studies raised the importance of building a rural cooperative economy and the re-aggregation of rural resources to improve their abilities to engage with current markets. However, how and at what scale should cooperative economy and collective action be restored, especially after the implementation of the rangeland household contract system, becomes a critical challenge requiring adequate attention from future studies.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

G and LW conducted field research in the case village from the Tibetan pastoral regions and drafted the paper, while LY conducted the fieldwork in the case village from Inner Mongolia. All authors contributed to the article and approved the submitted version.

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The Future of Transhumants' Sustainable Resource Use in Bhutan: Pressures and Policies

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Cattle and yaks in Bhutan are mainly managed in a transhumance system, grazing common pooled resources. This is, however, changing due mainly to policy changes and development pressure. The unequal land policies now restrict mobility for cattle-based transhumance by agro-pastoralists although it is expected to remain the same for the yak-based pastoralists. Essential public infrastructures also are being built in the common pooled resources, thus reducing the grazing areas for cattle and yaks alike. This study uses qualitative interview and focus group discussions in conjunction with administrative data and policy documents to understand the forces that increasingly lead to the decline of transhumance and see how it might change the grazing landscape and socialscape in the future. The study finds that grazing in the future will likely transform from an extensive to a semi-intensive system with smaller herd sizes for cattle-based agro-pastoralists. This is being achieved through interventions implemented by the livestock department, promoting crossbreeding with European dairy breeds. Transhumant herder turned sedentary smallholder farmers are fast adopting a sedentary lifestyle. This is changing not only the landscapes from grazing in large expanses of forest and open meadows to restricted semi-intensively managed smallholder farms with a possible impact on biodiversity. Crossbreds of European dairy cattle are fast replacing indigenous siri cattle of the *Bos indicus* type. Yak-based transhumance is expected to continue with favorable policies and other opportunities, including collection of the highly priced caterpillar fungus, *Cordyceps sinensis*. The socialscapes are fast changing for both highlanders as well as mid and lowland herders. Many of these places inhabited by herders are now connected by motorable roads, shortening their travel time to the nearest health facilities or shops from days to hours.

Keywords: transhumance, mobility, adaptation, sedentarization, cattle, yaks

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INTRODUCTION

Today, pastoralists globally, are faced with myriad challenges and opportunities arising from economic development, social change, climate change, conservation, and sedentarization policies, population growth, and war or conflicts (Behnke, 1983; Ellis and Swift, 1988; Fratkin et al., 2004; Nori and Davies, 2007; Galvin, 2009). Some of these challenges can have a catastrophic impact on pastoralists' livelihood either temporarily or long-lasting (Moritz, 2008; Scoones, 2008). It can constrain them from employing their adaptive strategies and deny them support for their sustainable development. As a consequence, pastoralists today are moving into the twenty first century with less ability to maintain their subsistence livestock economies than at any time in the past (Bonte et al., 1996; Fratkin, 1997; Ning and Richard, 1999).

In Bhutan, traditionally, cattle and yaks were both grazed in extensive systems, many often practicing mobile pastoralism. Local breeds of cattle called *nublang*, a *Bos indicus* type of Himalayan cattle breed and its crossbreds with Mithun (*Bos frontalis)* formed the dominant livestock breeds. The *nublang* cows are often crossbred with Mithun for better milk production, higher butterfat content, and superior draft performance. These breeds thrived well in this extensive system with minimal supplementary feeding. The only supplementary feeding farmers provided to milking cows were semiboiled turnip and radishes with the stems or maize flour and rice bran. In essence, these mobile pastoralists in Bhutan, as is the case anywhere in the world, utilize dry, poor-quality land that is often unsuitable for conventional agriculture and ephemeral resources and convert to food products such as milk, butter, cheese, meat, and hide. Because transhumance in Bhutan is based on the local cattle, mobile herders are the custodians of the cattle genetic resources, conserving the indigenous cattle breeds thus far (Namgay et al., 2014).

Further, it is evident that people created the range-landscapes they used for grazing their cattle and yaks. As landscapes are "the result of the action and interaction of natural and/or human factors" (ELC, 2000), rangelands in Bhutan are shaped by man for human and livestock use. It is plausible to claim Bhutanese pastoralists created the rangelands in Bhutan and mobile pastoralism formed the primary vocation of early Bhutanese. These are shaped by clearing and burning out undergrowth, a critical management practice for sustainable grass production. For example, Ura (2002) writes,

> Alpine rangelands in Merak, above 3,900 meters, were created several hundred years ago; according to its settlement history, the name Merak means "settlement created by burning out."

Similarly, rangelands in Tibet are claimed to be created by people through bush clearance as opposed to nature given (Miehe et al., 2009). Pastoralism and the nature of rangeland creation in Nepal have also been described in a similar fashion (Goldstein, 1974; Macfarlane, 1989; Banjade and Paudel, 2009). Mobile pastoralism was widespread and thrived in Asia's rangelands including the Himalayan ranges, for thousands of years. Pastoralism and transhumance in these regions occur in areas that are remote and forested and in open highlands, unsuitable for cropping, moving in tandem with forage availability and temperature shifts (Miller, 1995; Singh et al., 2013). Recent evidence suggests pastoralism in Tibet started some 8,000 years ago during the mid-Holocene climatic optimum (Miehe et al., 2009).

This literature evidence suggests that cattle herding with transhumance as the predominant system perhaps formed one of the primary vocations of earlier Bhutanese people. It is possible that the transhumant alpine yak system and cattle-based transhumant agro-pastoralism not only formed the oldest production sectors, but also happened to be the sector early theocratic and initial monarchic governance systems relied on for maintenance of the state system. It was not until other agricultural and non-agricultural alternatives became possible that people could establish more sedentarized lifestyles.

However, such systems are increasingly coming to an end amid many changes, including climate and policy. With the introduction of development plans in the 1960s, government subsidy schemes promoted crossbreeding of local cattle with European breeds, encouraging sedentary farming systems. This was done to increase both productivity per animal and overall milk production. Until 1998, a breed barrier was established such that jersey crosses were promoted in warm temperate to subtropic areas and brown Swiss cattle were promoted in cold temperate places. Since then, by popular demand from farmers, the breed barrier was removed, and jerseys became popular throughout the country. The state-owned farms breed these exotic cattle and supply breeding materials, mostly bulls, to farmers for crossbreeding with local cattle. In recent years, the government started procuring and promoting the use of sexed semen in farmer fields as well as government central farms to increase the crossbred female population.

The government policies on access to these resources consistently discouraged cattle-based interdistrict transhumance. The latest such policy is the Land Act of Bhutan (2007), which set 2018 as the definite year for cessation of interdistrict cattle migration (Namgay et al., 2017). The dominant policy narrative in Bhutan is that local cattle are low yielding, use large tracts of pasture as well as forest, and cause forest degradation; therefore, they need to be reduced or replaced with high-yielding exotic breeds that require smaller spaces and have higher milk yield.

These policies have a huge impact on the way the livestock are now raised and how rangelands and socialscapes are changing or likely to change. This study, therefore, examines the pressures and challenges mobile pastoralism face as a result of these changes and tries to comprehend how this might change the grazing landscape and socialscape in Bhutan among mobile pastoralists.

THEORETICAL FRAMEWORK: PASTORAL ADAPTATION

Today, the literature on adaptation is overwhelmingly associated with climate change and its effect on ecosystems and society and closely linked with resilience and vulnerability (Kates, 2000; Smit and Wandel, 2006; Nelson et al., 2007; Jerneck and Olsson, 2008).

Smith and Wandel (2006, p. 282) define adaptation in the context of human dimensions of global change as follows:

> "…a process, action or outcome in a system (household, community, group, sector, region, country) in order for the system to better cope with, manage or adjust to some changing conditions, stress, hazard, risk or opportunity."

Adaptation can, therefore, be defined as balancing between livelihood capitals within the space provided by ecosystems, tenure institutions, climatic conditions, and alternative economic opportunities to maintain a constant supply of goods and services to the actor units. In other words, it is an effort to survive or advance through smart management of internal factors of production in constant interaction with external factors based on informed decisions. Adaptation is a dynamic process occurring at differential scales, spatially and temporally, necessitating flexibility in the system to respond to changes and reduce negative impacts (Smit and Wandel, 2006; Galvin, 2009). Adaptation enhances system resilience and reduces vulnerability (Smit and Wandel, 2006; Nelson et al., 2007; Jerneck and Olsson, 2008).

Pastoralists, in general, are constantly adapting through seasonal migration, manipulation of herd size, sedentarization, commercialization, diversification, and adoption of alternative lifestyles wherever feasible, including emigration to urban areas (Niamir-Fuller, 2005; Smit and Wandel, 2006; Galvin, 2009).

Pastoralists' Adaptation Strategies

Pastoralists' adaptation strategies include seasonal transhumance (mobility), commercialization, sedentarization, diversification, and adoption of alternative livelihood options similar to their cropping farmer counterparts (Ellis, 1998, 2000). The changes or stressors impact adaptability differentially, affecting the poorer sections of the society the most. Pastoralists, with limited livelihood capitals, who depend heavily on natural resources, are often forced to abandon their livelihood as a consequence of these changes (Kates, 2000; Intigrinova, 2005; Niamir-Fuller, 2005; Nori and Davies, 2007; Pachauri, 2007), resulting in further marginalization. Some adaptation interventions, brought about by agencies, conflict with the acquisition of adaptive capacity of the poor and result in increased vulnerability and, hence, expel them away from their livelihood source altogether (Niamir-Fuller, 1999; Kates, 2000).

Diversification as an Adaptation Strategy

Pastoralists diversify their livelihood options, including sedentarization in peri-urban areas, to tap available opportunities. Some men, after settling near peri-urban areas, continue to keep pastoral cattle while women adopt additional trades in the urban market (Watson, 2010).

Adoption of diversification can both be a desperate coping strategy for the rural poor or spread income streams by wealthy households (Ellis, 1996; Start, 2001). Ellis (2000) calls it "diversification of necessity and diversification by choice." The majority of rural households practice diversification and engage in a range of livelihood portfolios because income from their main farming occupation alone is not enough to sustain the household. Often, income from other sources is much higher compared with income from their primary livelihood (Ellis, 1999). The existence of inter- and intra-community heterogeneity in well-being levels and, hence, a need to adapt through diversification is not always due to a lack of livelihood assets or capitals, but due to the absence of equitable access or entitlement to vital resources (Sen, 1982; De Haan, 2000; Davies and Bennett, 2007).

Pastoralists sometimes move into non-pastoral trades, often with total abandonment of pastoralism (Start, 2001; Smit and Wandel, 2006; Davies and Bennett, 2007; Galvin, 2009). For example, many Himalayan pastoralists have diversified and are now engaged in agriculture, trade, and tourism. Some integrate animal husbandry with agriculture. In an integrated system, livestock provide milk, butter, cheese, meat, and valuable inputs needed for crops, such as manure to maintain soil fertility and draft power to plow fields as well as pack animals for transportation during transhumance or for tourism services (Miller, 1995; McVeigh, 2004).

Sedentarization and Commercialization as an Adaptation

Sedentarization and settling, especially in peri-urban areas, is generally perceived to potentially enhance human capital through improved access to health care and educational opportunities. Sedentarization, either through government policies or of their own will, is a growing trend but has mixed impacts, particularly on pastoral women (Watson, 2010). In some African pastoral societies, although married couples may diversify with men continuing to go with animals leaving women to collect firewood or grow vegetables, female-headed households are likely to suffer further marginalization as a result of biased social norms that look down upon women with no husbands (Watson, 2010). In these societies, commercialization can have negative impacts on women and increases their vulnerability as the trend follows that, as herd sizes grow beyond a subsistence level, the economy of the herd becomes more of a business orientation and comes more under the control of men than women (Watson, 2010).

MATERIALS AND METHODS

Study Area

This study explored the changing grazing landscapes and socialscapes as a consequence of a multitude of policies and pressures in Bhutan. Bhutan is a small and mountainous country with a total geographical area of 38,394 km^2 (NSB (National Statistical Bureau), 2018). The country's landscape is dominated by mountain ecosystems and changes within a distance of 170 km from elevations of about 100 m in the foothills to more than 7,500 m above sea level. The country is largely agrarian with more than 69% of the population living in rural areas, relying primarily on agriculture. With as many as 80% of the members of the poor households engaged in agriculture, livestock plays a key role in shaping and strengthening their livelihoods. With little grown fodder, Bhutanese farmers depend extensively on crop residues and forest resources for cattle grazing and fodder collection.

The renewable natural resources (RNR) sector, comprising agriculture, livestock, and forestry sectors, together contributed around 15.89% to the gross domestic product (GDP) in 2019. Of these, the agriculture sector contributed 8.43%, followed by livestock and forestry sectors at 4.46 and 3.0%, respectively (DoL (Department of Livestock), 2020).

Data Collection and Analysis

This paper used some unpublished qualitative data collected earlier for a PhD research project. This is supplemented by administrative data, review of government office reports, policy documents, acts and rules, and other relevant literature.

The study administrative data and factors identified cover the whole of the country where transhumant mobile pastoralism and grazing in common pooled resources (CPR) are commonly practiced.

A total of 33 interviews (25 male participants, 8 female participants) and 3 focus group discussions were conducted with herders, experts, government officials, and local government authorities. The 33 interview participants comprised 24 migrating households and nine experts. They are now experiencing changes both in the policies and their influence on herding practices. The nine experts (six government and three non-government) were chosen based on their knowledge and experience in livestock development and environmental policies in Bhutan. The focus group discussions with 64 participants (40 male, 24 female) were also held to collect feedback and seek consensus among a wider audience on emerging issues highlighted during the interviews, such as factors contributing to the decline of local cattle, policy changes, and their adaptation strategies.

Purposive and snowballing methods were used to identify participants with prior experience in transhumant pastoralism and who understand the emerging issues (Noy, 2008). The snowballing technique is most commonly used in interdisciplinary qualitative social science research, wherein a key informant refers the researcher to others based on their knowledge (Noy, 2008).

All the interviews with herder informants and focus group discussions were conducted face to face in the national language: Dzongkha. Interviews with open-ended questions formed the core tool for this research in exploring herders' experiences and in eliciting issues (Tong et al., 2007).

All interviews and focus group discussions were recorded with a digital recorder and later transcribed and translated into English. Data analysis comprised coding, categorization, and thematization (Charmaz and Bryant, 2008).

The results are presented as a composite of excerpts from interviews and focus group discussions, a literature review, government department administrative data, and a critical review of policy and plan documents.

RESULTS

The Declining Trend in Indigenous Cattle Population as a Consequence of Development Policies

The following section provides the current scenario of the changing breed composition of cattle and the reasons that are the precursor to such trends. The interviews revealed changes to the cattle breeds and quality of the herd over the years. Most of the herders stated the overall herd composition of migratory herds have changed from herds being largely of *Nublang* (*Bos indicus)* and *Jatshams* [crossbred between pure Mithun (*Bos frontalis*)] to now include exotic breeds, such as jerseys, brown Swiss, and Holstein crosses.

The interview statements are substantiated by the cattle population trend over the years as shown in the graph in **Figure 1**. The overall cattle population has seen only a half a percentage point (0.50%) rise between the years 1994 and 2018, due mainly to the rise in the exotic cattle population. During the same period, the exotic cattle population increased manifold (269.54%) from 29,981 in 1994 to 116,733 numbers in 2018. However, the indigenous cattle population has decreased by more than a quarter (−29.40%) within 24 years. The exotic crossbred cattle are fast replacing indigenous breeds of cattle as a result of government policies and promotional programs favoring exotic as opposed to indigenous cattle breeds.

However, the same cannot be implied for yak population trends. Amid many fluctuations over the years, the yak population has, rather, increased by around 13% during the same period (**Figure 2**). The yaks do not have competing breeds of choice unlike the cattle. Although inter-regional differences exist in the quality of the yaks, due mainly to level of inbreeding and genetic degeneration, the breeds are not significantly different between yak-rearing districts in Bhutan.

These trends are a consequence of policies including the livestock breeding policy (more on this policy can be found in subsequent sections) that is seen as biased and grossly discriminatory against the indigenous breeds *Nublang* and *Jatsha-Jatsham*. Herders under the transhumance system seem to prefer local breeds for their hardiness—a crucial quality necessary for migration, good butterfat content, easy management, and good draft power usage. However, they are responding to policies and government programs and are now increasingly adopting exotic crossbreds suitable in sedentary farming systems.

Pressures on the Grazing Resources

Competition From Alternative Development Uses

Land competition from development and commercial agriculture, public infrastructure, systems change, a labor shortage, and youth and outmigration of men are contributing to the decline in pastoralism from the way it used to be.

Grazing resources used by transhumant agro-pastoralists, commonly held as CPR, including rangelands, today have come under immense pressure from competing uses. Rangelands continue to shrink in the name of development and are changing as a consequence of policies. Much public infrastructure is built in the rangelands, inter alia, local government offices, community centers, agriculture and livestock extension offices, forest range and park offices, gates, schools, village banks, and farm shops.

Additionally, today an increasing number of households are getting into contractual plantation of hazelnut plants with the Mountain Hazelnut ventures company. These areas previously formed some of the main grazing areas for cattle in the locality. The company website (www.mountainhazelnuts.com) indicates some 15,000 households setting up hazelnut orchards in areas that would be used for grazing their cattle.

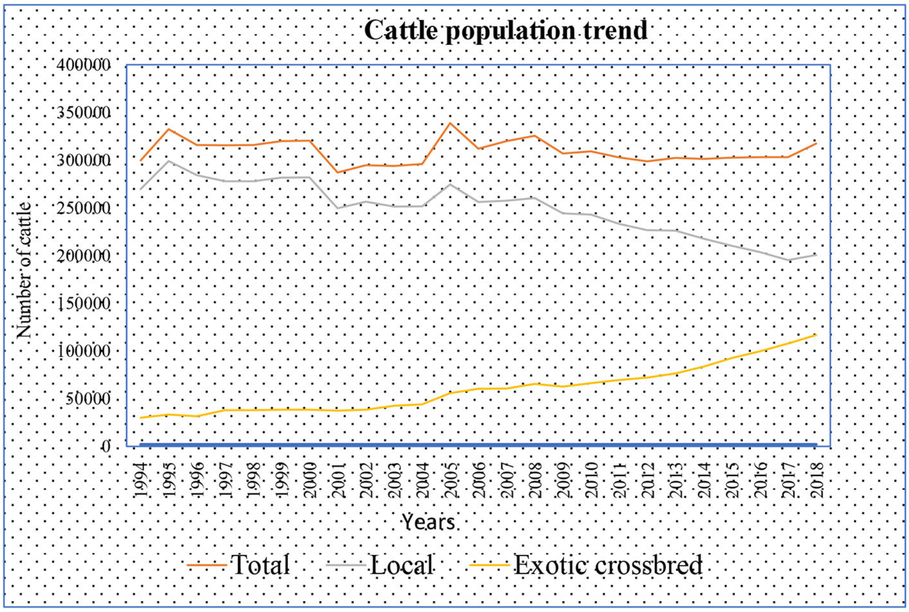

FIGURE 1 | Cattle population change.

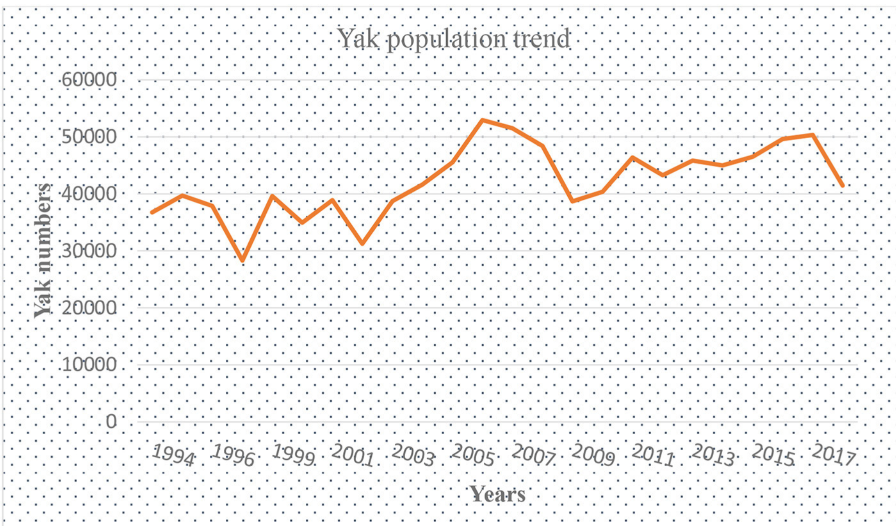

FIGURE 2 | Yak population trend.

Transformation in Transport System

With modern development, power tillers and tractors were introduced for tilling agricultural land. Construction of roads and farm roads into the villages took away the roles played by oxen for plowing and transporting goods during seasonal transhumant migration. Although usage of tractors is limited owing to the topography in large parts of the country, power tillers are gaining popularity. Many of the horses used by the pastoralists in carrying their household items during seasonal migration and later for transporting oranges to fetch cash have now been rendered redundant except for a few who are now engaged in transporting tourists and their logistics to camp sites. Many of these horses have now turned semi-feral.

Government initiatives with support from the Government of Japan have afforded a supply of farm machines at subsidized rates. In 2020, there were a total of 4,550 power tillers and some 30 tractors in Bhutan with the farmers and government hiring agency [Agriculture Machinery Center (AMC), personal communication and self-calculation], and there were only 16,820 horses [DoL (Department of Livestock), 2019] many of which lay unused.

Policies and Legislation Restricting Transhumance and Forest Grazing

Institutional reforms have transformed private, joint, and common grazing areas into state lands and imposed several restrictions on areas commonly used for grazing by transhumant pastoralists.

According to two agency experts, *tsamdro* (local term for grazing land or pasture) titling accorded during the pre-monarch era (before 1907) and later under monarchic rules were subsequently reflected in the national land records. This is said to have happened when the national assembly in 1953 accorded full private ownership rights of *tsamdros* to individual and joint ownership, similar to other land categories. However, the first land law of the country—the Land Act of Bhutan of 1979—in the words of one agency expert, "diluted the ownership of *tsamdros*" and put an end to tax collection. Hence, instead of tax collection, only permit/lease fees were collected, indicating the nationalization of *tsamdros*, converting herders' *tsamdro* ownership rights to mere usufructuary rights.

One herder key informant who lived through these changes explains how these changes took place:

> "…earlier it was tax, then it was permit with a fee of about Ngultrum [term for Bhutanese currency] 100...It was Ngultrum 100 per annum per household irrespective of the size of tsamdro, either big or small, as long as it is registered as tsamdro in your name." (Herder_33)

Another male herder reiterated the same and explained that, since 2008, the government has also stopped collecting the Nu. 100 permit fee:

> "…we have been paying taxes and fees, but it has been now three years, *gewog* [local government] office did not collect that either. Until that time we have been paying and getting the receipt." (Herder_27)

This was an indication that the *tsamdros* have once again been nationalized under the new land law (Land Act 2007).

The following section describes different laws and policies that have relevance and how each of these has impacted the transhumant pastoralism in Bhutan.

Forest Act of 1969

One of the first legislations in Bhutan, the Forest Act of 1969, restricts cattle grazing only in the reserved forest and allows it in other forest areas with fees.

This law, however, banned the use of fire, which has resulted in the spread of rhododendron shrubs overtaking what was once open rangelands and has reduced grazing areas. Traditional rangeland management practices meant clearing these bushes and burning them to allow grasses to grow. Herders burnt bamboo and rhododendron shrubs periodically to create space for the regrowth of other species. Such periodic burning is described as "brogshed" by Ura (2002) and the undergrowth in chirpine forest was regularly cleared by fire. The *Yardrog* rangelands of Merak in northeastern Bhutan benefitted from such burning because the fire promoted the growth of fresh bamboo shoots and grasses (Chophyel, 2009).

In other areas, losing grazing areas to pine forest and a consequent reduction in grazing areas resonated strongly among herder participants during the focus group discussions. The participants believed that restrictions by the forest department on clearing bushes and burning has resulted in pine trees invading their prime grazing areas. The participants said that no grasses grow under the pine trees.

A male participant in his sixties said the following:

> Earlier we use to clear the camp sites and grazing areas by cutting and burning the bushes. Now because of the forest restrictions saying its environment, trees are important and, not allowed to do this or clear that; these trees are taking over even our agricultural fields.

The same point was mentioned during another focus group discussion. Many herder participants believe the restriction by the forest department on their traditional pasture management practices is converting their good pastures to pine forests.

A male participant in his fifties said the following:

> Well, earlier…as soon as the herd reaches here, we clear some of the bushes and burn them, so we used to have huge open areas for cattle to graze. Now, because we are not allowed to cut or burn the bushes, the pine trees take over the open areas and there is nothing under those trees to graze.

This trend was evident from the researcher's observation in all the study areas. Many areas in and around their villages, which the village elders indicated had been used for growing buckwheat in the past, are now all covered in thick pine forests. Most pine trees in the village premises are still young, meaning these are not old forests but new growth in what used to be agricultural fields, grown after the ban on slash-and-burn practices came into effect.

Forest Policy of 1974

The first written policy in Bhutan is the forest policy of 1974. One of the principles in the earliest forest management practices, inter alia, is to meet the requirement of forage for cattle. However, the policy notes that grazing rights being with the local people is damaging the soil, vegetation cover, and forest regeneration process. Therefore, the policy foresees acquisition of such rights by the government and allowing controlled grazing through payment of taxes.

Draft Pasture Policy of 1985

The draft pasture policy of 1985, although never formalized, is being practiced in vogue. Among many other interventions, such as developing pasture with exotic fodder species, the draft pasture policy, right in the objective mentions nationalizing grazing rights and redistributing them through leases of 30 years at a stretch. The policy puts a cap on the extent of pastureland a household can lease based on the livestock units it holds. The policy, however, does not mention putting restrictions on interdistrict transhumance movement. Apparently, the policy draws its inspiration from the Land Act of Bhutan of 1979 (RGoB (Royal Government of Bhutan), 1985).

Forest and Nature Conservation Act of 1995

Article 30, sections A–C, indicates permitting regulated grazing in government-reserved forests with penalties or seizure if trespassing into areas closed to grazing.

Forest Policy of 2008

Although the policy states that Bhutan's forest should benefit its people and mentions poverty alleviation a couple of times, save for ensuring subsidized rural timber, there is no specific mention of how the forest would benefit grazing or livestock keepers. The only mention of livestock is, in highlighting the importance for watershed management, it purports watersheds' pivotal role in supplying a wide range of goods and services for, among others, pastoral pursuits and in sustaining the livelihoods of upland farmers and grazers.

Department of Livestock's 12th Five Year Plan (12FYP)

The current livestock development plan also is biased toward exotic breeds over local breeds; thus, all allied services are also directed toward crossbreeding and conventional/modern semi-intensive/intensive farming systems. The overall budget for development of livestock in the 12FYP (2018–2023) is BTN 904 million (∼USD 12.9 million). The bulk of this development budget is meant for improving livestock breeds, including cattle; improving nutrition and health; and providing a subsidy on building improved housing. Although there is a separate budget of BTN 317 million (∼USD 4.5 million), equivalent to 35% of the total plan outlay, specifically for a highland development program targeted at yak herders, there is no specific mention of a budget for mobile pastoral cattle. The remaining budget is meant for improving breeds, nutrition, health, research, and development services of all the other livestock species, including cattle, in a conventional way [DoL (Department of Livestock), 2019].

Draft Livestock Policy

The draft livestock policy of Bhutan of 2012 only recognizes the existence of transhumant systems in the preamble and does not make a single mention in the subsequent main texts (MoAF (Ministry of Agriculture and Forests), 2012).

The policy, de facto, promotes crossbreeding of most livestock and poultry species with exotic breeds to increase production. Exotic cattle breeds, especially jersey, are preferred over local indigenous cattle: *Nublang*, a siri cattle of the *Bos indicus* type. Jersey crossbreds are, however, not suitable for long-distance travel on foot—necessary for transhumance.

The government development plan mentions increasing the crossbreds [DoL (Department of Livestock), 2019]. All technical and fiscal incentives are directed at increasing the population of the exotic breeds over local breeds (MoAF (Ministry of Agriculture and Forests), 2019).

Increasingly, government efforts are being made to enable sedentarized farmers to take advantage of modern technologies and farm inputs. Breeding materials, such as jersey bulls and imported semen, conventional as well as sexed, are being distributed free of cost to communities. Other subsidies, including the cost of materials for constructing improved sheds and silo pits and integration with the bio-gas system, are subsidized by the government. Improved fodder seeds are distributed, encouraging establishment of grown pastures as opposed to grazing in open meadows or forest. In the 12FYP (2018–2023) government targets are to establish about 26,614.00 acres of improved pasture and winter fodder [DoL (Department of Livestock), 2019].

The trend is also to encourage farmers to form groups, cooperatives, and federations. Many of the government subsidies are targeted to groups and less to individuals. In 2018, there were 347 farmer groups and 57 cooperatives, including 582 semicommercial and 361 commercial-scale livestock farms. Women represent 20% and 18% in membership and leadership roles, respectively (Namgay, 2017).

Livestock Act of 2001

The livestock act (2001) mentions standards to be followed in breeding and operation of farms with restrictions to prevent incursion of diseases. Except for the need to follow certain rules to contain/prevent disease spread, the act does not make any mention of whether transhumant pastoralism is discouraged (RGoB (Royal Government of Bhutan), 2001).

Land Policy of Bhutan of 2007

The land policy of Bhutan (2010) provides for leasing of state reserved forest (SRF) land for agriculture and livestock production. It does not specify whether a proponent from a different district leases SRF for transhumant pastoralism (NLCS (National Land Commission Secretariat), 2010).

Land Act of Bhutan of 2007

Chapter 10, article 235, of this act mentions deleting all *tsamdro* (grazing land) rights from the *thram* (land title document) and reverting the land back to the government if it is in an urban area or to government reserved forest land if in the rural areas. Further, article 236 states that the reverted *tsamdro* in rural areas shall be converted to leasehold, and that in *thromde* shall remain as government land. Article 240 provides for the leasing of reverted *tsamdro* to individuals or communities owning livestock with preference being given to previous rights holders. Article 247 requires that grazing and pasture development on *tsamdro* be permitted based on a management plan with the department of forests, the department of livestock, and the lessee responsible for its preparation.

The Land Act of Bhutan of 2007 is one of the earliest forms of legislation that sets a definite time within which the grazing rights held by livestock keepers, including transhumant herders, are to be nationalized. The law sets 2018 as the year within which the nationalization should happen (RGoB (Royal Government of Bhutan), 2007). It further states that subsequent leasehold rights shall only be granted to residents domiciled in a particular district, barring transhumant pastoralists who traditionally moved between two or more districts seasonally.

Section 239 of the Land Act of Bhutan of 2007 states the following:

> After 10 years from the date of enactment of this Act, Tsamdro shall be leased only to a lessee who is a resident of the Dzongkhag where the Tsamdro is situated.

National Biodiversity Strategies and Action Plan Bhutan (NBSAP) of 2014

The NBSAP identifies overgrazing as one of the direct pressures among the threats affecting biodiversity.

Forest and Nature Conservation Rules (Amendment) of 2020

The amended Forest and Nature Conservation Rules (2020) make no mention of grazing or transhumance use for livestock production except for classifying the type of lands and restrictions for lands provided by the National Land Commission for purposes including lease (MoAF (Ministry of Agriculture and Forests), 2020).

DISCUSSION

Declining Indigenous Cattle and Transhumant System as a Consequence of Development and Policy Reforms

The persistent forest protection and environment conservation policies and legislation in Bhutan have steadily tightened access to forest grazing resources. The dominant narratives of the effect of cattle on the environment have influenced the livestock development approach, restricting mobility with a preference for a more intensive way of livestock farming. Restrictions on traditional management practices, such as bush clearing and burning, have resulted in grazing pastures being overtaken by unpalatable bushes, thus reducing effective grazing areas and increasing pressure on limited rangeland areas suitable for grazing. Lessons from the neighboring countries in the region indicate adverse impacts on both vegetation and livelihood in the alpine ecosystem as a consequence of restrictive environmental rules (Nautiyal and Kaechele, 2007).

Despite the fact that pastoralism is a finely adapted production system, suited to highly variable environmental conditions, thus presenting potential compatibility with wildlife conservation, production is highly compromised owing to reduced access to grazing resources, civil unrest, and climate change (Gerber et al., 2010).

The dominant view among policy makers of developing nations that local people are to blame for environmental degradation is a perceived notion rather than evidence-based (Leach and Mearns, 1996). Their view developed through Western education, and supported and reinforced by donor agencies, influences the image of the environment and the urgency to protect areas for conservation. These exaggerations of environmental degradation, supposedly caused by the herders and local people's access to natural resources, have become a common belief among some foresters and environmental agencies (Chambers, 1997). These crisis narratives have helped develop frames and shape the mindset of some policy makers (Leach and Mearns, 1996).

Recent reviews reveal the outcomes of livestock grazing on forest are mixed, indicating benefits as well as the effects of forest grazing. The much cited reason, overgrazing, in conservation documents in Bhutan, even if there is a certain degree of truth, cannot solely be blamed on grazing by cattle. Grazing overlap and competition with wild ungulates are also reported in Bhutan (Gyamtsho, 2000).

Consequently, grazing areas, including rangelands, that were managed by transhumant herders with planned herding and controlled burning, thus mimicking nature and making livelihoods out of ephemeral resources, are likely to be converted to wilderness. This could possibly lead to deterioration of the social fabric, customs, and indigenous rules and regulations governing these grazing rangelands (Herrera et al., 2014).

With the emerging political ecology, aside from the dominant proconservation discourses, there is often no scientific data on the extent of degradation or the main reasons causing degradation (Leach and Mearns, 1996; Chambers, 1997). However, there are repeated portrayals of pastoralists and rural people (especially ones located between state-created protected and conservation areas) as agents of environmental destruction in public discourse through media and policy discussion circles that has changed the frame of public perception (Lakoff, 2004; Brower, 2008). These trends, which Lakoff calls "ignoring the fact and accepting the frame," have led to an increase in the number of protected and conservation areas in developing countries, resulting in an upsurge in wildlife populations, causing increased incidences of human–wildlife conflicts, leaving the rural populace, including TAP herders, worse off (Blench, 2005).

The creation of protected areas, conservation areas, and biosphere reserves has resulted in reduction in grazing areas in the Indian Himalayas as well, thereby increasing stocking density per unit areas (Nautiyal et al., 2003). Competition and exclusion through enclosures has also occurred in Ladakh, where military enclosures have reduced grazing areas and caused an increase in stocking density per unit areas (Namgail et al., 2007).

This attenuation of pastoralists' grazing resources is further exacerbated by land grabs by national commercial cropping firms and foreign ownership of land by capital-rich nations with governments of poor nations giving concessions to attract investment (Cribb, 2010; Robertson and Pinstrup-Andersen, 2010; Zoomers, 2010). This trend is likely to have food security implications for the marginalized groups, including pastoralists (Robertson and Pinstrup-Andersen, 2010; Zoomers, 2010).

Converting Transhumant Herds Into Semi-intensive, Stall-Fed Farms, and Changing Grazing Landscape and Socialscape

Pastoralists in general and particularly in Africa are politically marginalized on top of being poverty-stricken and vulnerable to livelihood shocks (Eneyew, 2012). However, transhumant pastoralists in Bhutan are a bit different. Although, owing to geoclimatic conditions, agriculture-based livelihood choices are limited, there is no obvious political marginalization. No categorization of citizens into minority or indigenous groups or political dominance exists in Bhutan. Citizens enjoy equal status as a Bhutanese, irrespective of their ethnicity or livelihood choices.

Although grazing by pastoral animals in the forests has several benefits, in terms of biodiversity conservation, reduced soil erosion and increased soil quality, improved air and water quality, better plant diversity, increased level of control on exotic (weedy) grasses, adding manure to the nutrient cycle, and seed dispersal, pastoralists face a number of issues accessing rangelands, and states increasingly encourage them to sedentarize in Lebanon (Sarkis et al., 2019).

Rangelands, home to herders, grazed by livestock and wildlife, and defined predominately as grasslands, are undergoing unprecedented changes worldwide. These grazing resources are being converted to urban centers and farms to satisfy the growing need of burgeoning human populations. Changing consumer preferences demands a shift from a traditional subsistence system to more market-orientated commercial production. The changing system, however, questions economic as well as environmental sustainability (Galvin et al., 2016).

The government policy in Bhutan encourages the raising of exotic cattle breeds with stall-feeding practices aimed at improving the income of rural folks, including those transhumant pastoralists. However, the overriding narrative is different than is implied in the African continent. Although ease of governance, provision of services, and improving the quality of life of pastoralists are dominant reasons for settling them in Africa (Eneyew, 2012), in Bhutan, they are blamed for keeping large herds thought to be detrimental to the environment. No scientific evidence exists as yet that proves overgrazing by pastoralists keeping local cattle with larger herd sizes causes environmental damage. These policies draw on broad narratives applied globally to mobile pastoralism wherein they are blamed for keeping large herds supposedly causing overgrazing, deforestation, etc. (Fratkin and Mearns, 2003).

Bhutanese transhumant agro-pastoralists are fast adapting to the changes. Although yak herders, favored by the law (RGoB (Royal Government of Bhutan), 2007), albeit a declining trend, continue the traditional transhumance practice, cattle-based agro-pastoralists have almost abandoned mobility and have settled in their permanent residencies. Transhumant agro-pastoralists have not only lost the opportunity to graze in subtropical *tsamdros* but also any opportunity to engage in orange business during the winter months (Namgay et al., 2014). They now increasing adopt stall-feeding or local grazing with exotic crossbreds and are increasingly engaged in vegetable production. Although climate change is a major global concern with livestock systems as both the cause and victim as is the case in many developing countries (Thornton et al., 2009), there is no sufficient data or literature to make any claim either way in Bhutan. It is, however, clear that exotic crossbred cattle will replace the native cattle breeds substantially. Unless conservation efforts are strengthened, a well-adapted and resilient breed such as *Nublang* cattle appears likely to disappear.

Although pastoralists in central Asia use the off-farm income of family members to buy more animals and increase their flock size (Kerven et al., 2011), in Bhutan, the off-farm income of family members are being used to buy improved cattle and settle out of transhumance practice. However, similarities in ownership of pasturelands exists between central Asian agro-pastoralists and Bhutanese transhumant agro-pastoralists. They never had ownership of the pastureland de facto. Although Bhutanese pastoralists have had pasturelands registered in their names, which they thought was ownership, the true ownership, de jure, always rested with the state and was held in usufructuary rights.

A similar decline in pastoralists' mobility and their increasingly adopting sedentary farming were observed in Kazakhstan for various reasons. It is also noted that flocks that did not practice seasonal movement had to graze in the overgrazed pasture in the locality and were poorer in growth and production (Kerven et al., 2004).

In the face of rising demand for dairy products and meat and climate change effects, pastoralists, the custodians of indigenous, locally adapted cattle breeds, should be supported. Supporting sustainable pastoralism suited to local environments would contribute to seven of the 17 sustainable development goals (SDGs); SDG 1: No poverty, SDG 2: Zero hunger, SDG 3: Good health and well-being, SDG 8: Decent work and economic growth, SDG 12: Responsible consumption and production, SDG 13: Climate action, and SDG 15: Life on land (FAO, 2020).

Scoones and Nori (2020) draw a parallel between how nations are having to adapt in the face of the current global Covid-19 pandemic with how pastoralists have always adapted under uncertain environment, climate, and policy conditions. Pastoralists, by virtue of living in a disequilibrium environment, having to triangulate various sources of knowledge and advice from experts, modern and traditional, to make the most reliable decisions in the face of uncertainty, resemble the current situation of governments around the world dealing with the uncertainty of the Covid-19 outbreak (Scoones and Nori, 2020). This teaches leaders a lesson, something that nations could learn from each other's experience and perhaps learn from pastoralists experience of adapting and living with uncertainty. However, because the cattle-based transhumant agro-pastoralists are now losing their adaptation tools or tactics, most importantly mobility, it is not certain how well they will adapt to variabilities, inter alia, market and climate.

The current efforts of technical departments in Bhutan are in line with Kristjanson et al. (2010), focusing on the three main areas to enhancing productivity of smallholder livestock keepers: feeds, breeds, and health. More attention now needs to be paid to other interventions, such as improving crop–livestock interactions in mixed smallholder farms, livestock water productivity, carbon sequestration on rangelands, and efficiency of farm animal labor, to harness the ability to increase the productivity of these smallholders (Kristjanson et al., 2010).

This multitude of factors and changing policies and climate necessitate transhumant agro-pastoralists to adapt quickly. This is not only going to transform the grazing landscape, but also the socialscapes—the way communities interact and play roles in society. Grazing landscapes will change from grazing in community pastures, open rangelands, and meadows to being tethered or grazed in the homestead-grown pasture or stall fed. The older practice and social fabric of neighbors grazing cattle in communal pastures, singing, and playing together will likely disappear. As much as the government expects them to work in groups and cooperatives, many of these induced institutions do not succeed in maintaining the traditional communal bonds and community vitality. The households would now be more individualistic, aiming to increase their production and generate more money. However, with limited land holding and poor feeding management practices now compounded by a labor shortage, it is not clear how settled pastoralists would be able to capitalize on sedentary farming with an exotic crossbred livestock and market economy.

In traditional pastoral societies, men own more cattle than women (Kristjanson et al., 2010). This is understandable when implied in the Bhutanese context, as in the pastoral system, herders need to stay in faraway places in the forest, often having to climb trees to lop fodder for young stock in the camp. This places women in a disadvantaged position compared with men. This is not so when they change and adapt to intensive/semi-intensive systems. These latter farms are near the homestead, using improved grasses, and expected to give a higher yield. These farms, when integrated with bio-gas systems, not only save labor by avoiding having to go to the forest and climb trees, but also sequester carbon and manage GHG more efficiently. The GHG from manure is trapped and used in the kitchen for cooking purposes. Integrating farms with bio-gas systems also save on fuel wood and other household energy expenditure. Because these farms are closer to the villages, this provides for a level playing field for women.

Transhumance is necessitated by seasonal environmental variability and resource availability. The practice resonates with that of rotational grazing, thus avoiding overgrazing (Aryal et al., 2018). In places where there is better temporal distribution of moisture and suitable temperature favoring year-round pasture growth, sedentary farming is recommendable. Himalayan high mountain areas are cold, dry, and frost-bitten during the winter months, posing a challenge to sedentary farming. Therefore, without proper housing and conserved forage, the condition and productivity of animals will diminish drastically during winter months. Advocacy, education, and training vis-à-vis interventions will need to be promoted on proper housing and fodder conservation during summer to give proper protection and nutrition in winter months.

It may not warrant the all out closure of transhumant movement and expecting every herder to adopt a sedentary lifestyle. An inclusive participatory process could have afforded choices to households to either adopt a sedentary lifestyle or continue with transhumance. The shortage of labor is already forcing some households to abandon transhumant movement and adopt sedentary farming. Political decentralization, proper coordination, and inclusive participatory discourse would result in more equitable distribution and sustainable management of rangeland resources and livelihood choices (Herrera et al., 2014).

Although the policies and interventions are intended in good faith, it is not clear how uniformly every pastoralist household would adopt and take advantage of the government subsidies. Given that the subsidies are uniform as opposed to the spatial heterogeneity in the households' response system owing to the variability in the capitals, how well every pastoralist household adopts it is yet to be proven (Thornton et al., 2009). What is perhaps of importance is to assist the pastoralists with marketing of their products. Government and international agency interventions in building capacity of the pastoralists in sustainable livestock management, value chain management, and marketing would result in higher income for pastoralists and better outcome to the environment as a result of improved management practices (Kerven, 2010).

As much as there are commonalities between sedentary agrarian farming and pastoralism (including transhumant production systems), there are key differences in both their social relations and productive forces (Scoones, 2020). Perhaps because most professionals and policy makers come with background on settled agriculture from universities and lack in-depth understanding of transhumant pastoral production systems, policies and interventions always target discrediting their practices.

CONCLUSION

Bhutanese transhumant agro-pastoralists are adjusting to changes brought about by development and environmental conservation policies. This is changing both grazing landscapes and socialscapes. Many of the erstwhile *tsamdros* would likely turn into wilderness although some would be leased by residents domiciled in particular districts as pastureland. A majority of the transhumant agro-pastoralists have already sedentarized, and others would soon follow suit. This would change the whole social fabric with new outlook and approach toward cattle raising. Many of them would now raise exotic cattle and get into milk groups and/or cooperatives.

Although this may have seemingly had a negative impact economically on those who have had access to larger grazing areas and not faced labor shortages, for others, these developments are coming in handy. Many rural communities have faced acute labor shortages with children being in school and/or having adopted an urban lifestyle. Bhutanese rural communities are turning *youthless* and *toothless*. It is becoming increasingly difficult to find people to go after the animals. As villages run short of farm labor, youth with some schooling are emigrating out of villages into the towns, looking for jobs and, thus, contributing to unemployment statistics. This is a concern for the government to reform the education system to incorporate more vocational learning into the system to make young people employable and create employment opportunities.

On other hand, within the limitations of topography and fragmented land holdings, agriculture in Bhutan has to transform toward more use of technology to make it easy and attractive to youth.

Adopting a sedentary system would also improve children's attendance at school. In the past, some children cut short their school attendance to accompany their parents while migrating south with their cattle. As a result, some children do not get to study beyond primary schooling.

5Yak herders are also facing the challenges of labor shortages, reduced grazing areas and climate change impacts. However, they continue to hang on because of favorable government policies as well as the incentive of collecting caterpillar fungus, *Cordyceps sinensis,* worth more than 1,000 USD per kilogram. However, the distribution of such caterpillar fungus is not uniform in all highlands. Therefore, the well-being of yak-based pastoralists when such incentives are absent has to be considered, and opportunities need to be created.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Charles Sturt University Human Research Ethics Committee. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

KN did data collection, analysis and write up. JM and RB supervised the research, contributed in design and structure of the article, and coedited the manuscript. All authors contributed to this article and approved the submitted version.

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REVIEW
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Pastoralism at Scale on the Kazakh Rangelands: From Clans to Workers to Ranchers

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Eurasia contains the world's largest contiguous rangelands, grazed for millennia by mobile pastoralists' livestock. This paper reviews evidence from one Eurasian country, Kazakhstan, on how nomadic pastoralism developed from some 5,000 years ago to the present. We consider a timespan covering pre-industrial, socialist and capitalist periods, during which pastoral social formations were organized in terms of kinship, collective state farms, and private farms and ranches. The aim is to understand how events over the last 100 years have led to the sequential dissolution and re-formation of the social units necessary to manage livestock across a wide expanse of spatially heterogenous and seasonally variable rangeland ecosystems. It is argued that the social scale of extensive livestock management must be tailored to the geographical scale of biotic and abiotic conditions. The paper starts by pointing out the long duration of mobile pastoralism in the Kazakh rangelands and provides an overview of how events from the late 17th C onwards unraveled the relationships between Kazakh nomads' socio-economic units of livestock management and the rangeland environment. At present, mobile animal husbandry is not feasible for the majority of Kazakh livestock owners, who operate solely within small family units without state support. These reformulated post-Soviet livestock grazing patterns are still undergoing rapid change, influencing the composition of rangeland vegetation, wildlife biodiversity, and rates of carbon sequestration. By concentrating capital and landed resources, a minority of large-scale pastoralists have been able to re-extensify by combining mobility with selective intensification, including an increased reliance on cultivated feed. Current state and international efforts are leaving out the majority of small-scale livestock owners and their livestock who are unable to either intensify or extensify at sufficient scale, increasing environmental damage, and social inequality.

Keywords: pastoral mobility, Kazakhstan, kinship, Soviet Union, history, environmental impacts, nomads

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INTRODUCTION

The Eurasian rangelands contain spatially heterogenous, seasonally variable and climatically unstable natural resources extending over large geographical scales (Matley, 1994a). Over millennia, humans have been able to exploit these resources by matching the geographical scale of environmental variability with appropriate socio-political institutions for herding domesticated grazing animals on an extensive basis. These rangelands comprise the world's largest contiguous area of grazing (Babaev and Orlovsky, 1985; Mirzabaev et al., 2016), comprising 25% of the world's total rangelands and over 6% of the total world land area (FAOSTAT "permanent pasture") (see **Figure 1**).

At 1.9 million km^2 (FAOSTAT, 2020), pasture constitutes 86% of the agricultural land area of modern Kazakhstan. Most of this pastureland is semi-arid to arid, receiving <300 mm precipitation per annum (often in the form of snow rather than rain). The pastures cover multiple ecological zones, from sandy desert dominated by woody shrubs and ephemeral spring bulbs, to short and long-grass steppes on the plains, and alpine meadows grazed by livestock in summer at altitudes of up to 3,000 m (Gilmanov, 1996; Asanov et al., 2003; Van Veen et al., 2003). The climate is severely continental, with very cold and snowy winters in which temperatures may fall to −30C, and hot dry summers with maximum temperatures of 50C (ibid.). A defining feature of much of the pastureland is that arable agriculture is impossible without irrigation.

ARCHAEOLOGICAL EVIDENCE

Archaeological evidence indicates that mobile pastoralists and their livestock have occupied these lands for at least 5,000 years (Frachetti et al., 2012). The Eurasian region was the locus for the domestication of goats, sheep, horses, and Bactrian camels (Larson and Fuller, 2014; Taylor et al., 2020) between 10.5 and 4 thousand years ago. Recent interdisciplinary research by archaeologists, climate scientists and ecologists is uncovering more about the complex relationships between nomadic migrations, settled farming, climate change, and environmental conditions in the last millennia–"as scholarship focuses on the ways in which pastoralists, of various degrees of mobility, exploited geographically variable, and annually shifting climatic conditions to find pasture for their herds" (Brooke and Misa, 2020, p. 3). Since pre-historic times, nomadic pastoralist groups have tracked climatic changes and vegetation heterogeneity across ecozones, seasonally moving their livestock long distances latitudinally, shorter distances altitudinally (Khazanov, 1984; Gilmanov, 1996; Frachetti et al., 2012, 2017), or made relatively short-distance moves combined with significant use of foddering (Ventresca Miller et al., 2020a). Archaeological research in Kazakhstan suggests that in the prehistoric past, "pastoralist mobility was likely similar to what we see in the ethnographic record: seasonal mobility patterns of variable distance that brought populations between known ecological zones as they seasonally came into various stages of productivity" (Frachetti, 2015, p. 9).

The floral and faunal biodiversity and landscape conditions now present in the Eurasian rangelands is an outcome of millennia of human use through mobile livestock husbandry (Spengler, 2014), in combination with climate change, the adoption of new technologies, and changing socio-political institutions. In the human migrations of mixed herding and farming "sheep led the way" (Frachetti et al., 2012, p. 15) between 5000 and 2000 BCE[1] and "…while climate certainly played a role, steppe cultures forged the pastoral systems that would exploit variations in the ecological uniformity of the grasslands. In so doing, they set in motion forces of anthropogenic change…" (Brooke and Misa, 2020, p. 17–18).

Against this archeological background, this paper examines the historical record over the last two centuries and outlines how pastoralist livestock management and land use systems in Kazakhstan have been altered by changes in socio-political institutions and economies. We argue that the geographical scale of environmental heterogeneity within the temporally and spatially varied climate regime of Eurasia has required particular kinds of social organization to effectively exploit rangeland resources. The social scale of extensive livestock management has had to match the geographical scale of livestock mobility required by the biotic and abiotic conditions. The present-day conditions on the Kazakh rangelands are the result of interactions between humans and livestock stretching back millenia. Sustaining the rangeland heterogeneity will require livestock-keepers to continue operating at scale, as documented by the environmental impacts of current declines in livestock mobility.

A Century of Dynamic Human Influence on the Kazakh Rangelands

Starting with the early written record, we outline a chronology of three national socio-political upheavals over the last 100 years, each of which led to pertubations in the socio-political organization of pastoralism in the rangelands. In the 18th and 19th centuries, Kazakh pastoralists practiced pre-industrial nomadism, characterized by localized kinship-based production units operating within a hierarchical political organization. In the early 20th century these institutional arangements were forcibly displaced by a collectivized socialist system in which the state assumed responsibility for supporting mobile husbandry. In the late 20th century, state socialism was replaced by a capitalist economy in which individual families employed private economic resources to maintain livestock mobility.

This century of changes in livestock management has left lasting effects on the rangeland ecology and on the pastoralists' economic, social and cultural life. The conclusion speculates about the changes that may be expected in the near future as a result of current institutional arrangements and management practices.

CLANS, CLIENTS AND SOCIAL STRATIFICATION

From the earliest explorers to present-day social scientists, descriptions of Kazakh social organization and customs have referenced "clans." In this review, we use the generic term with an intentional absence of deep enquiry into its often subtle and changing meaning. Outsiders' interpretations of what is a "clan" [*ulu* or *ru* in Kazakh) has varied through historical periods, has been incorporated into opposed politico-ideological agendas, and is still debated among contemporary social scientists—particularly political scientists and social anthropologists (e.g., Schatz, 2004; Collins, 2006; Sneath, 2007). No doubt the concept

[1] BCE is Before Common (or Christian) Era, formerly termed BC.

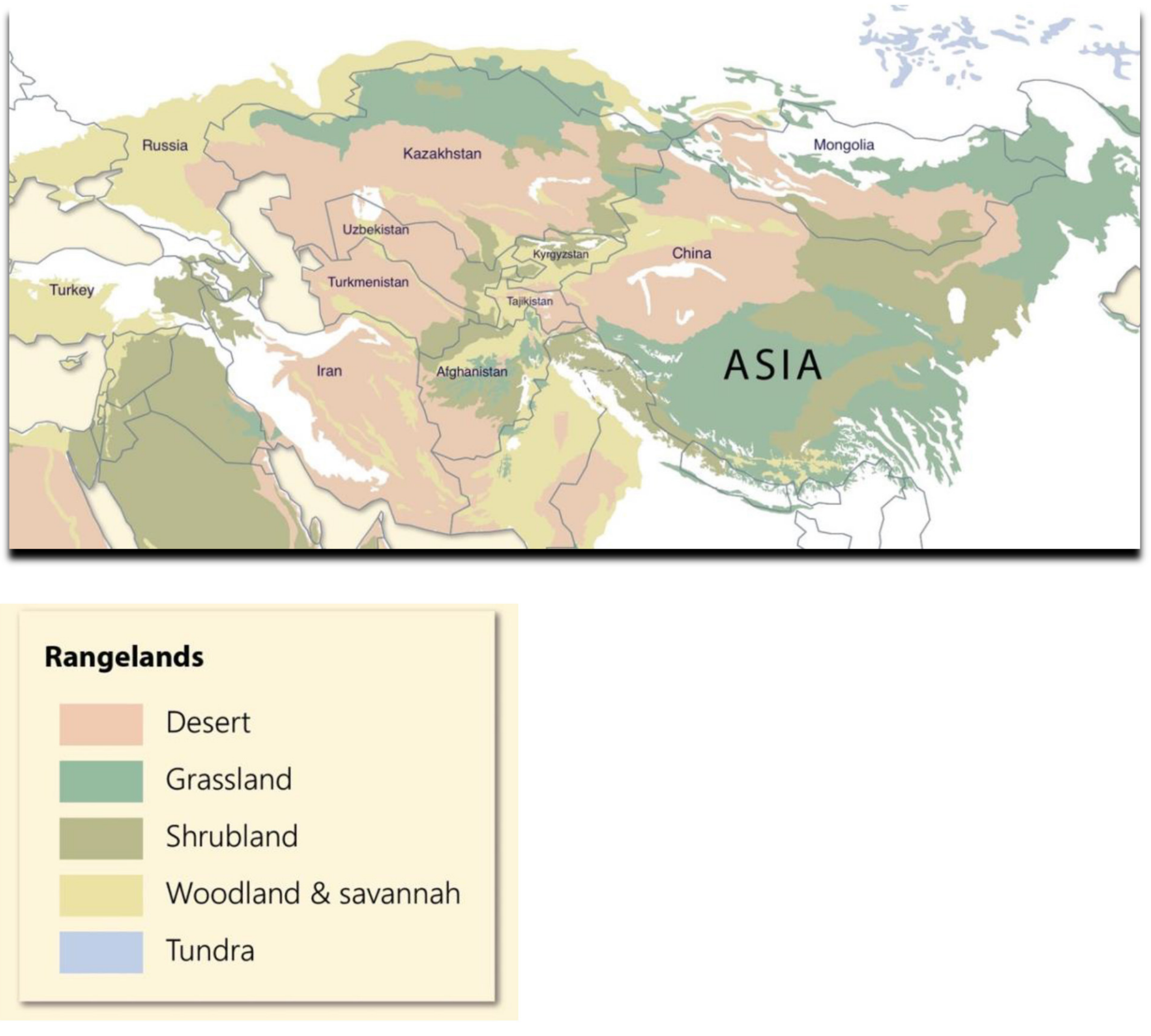

FIGURE 1 | The main types of rangeland in Eurasia Source: https://www.grida.no/resources/13199.

has undergone similar internal shifts in meaning throughout Kazakhs' own historical experiences.

Earliest written accounts by Russians about Kazakh clans (e.g., Levshin, 1832) were initially summarized in English language works such as Hudson (1938), and later in Olcott's magisterial work (1995). In the context of the social organization of Kazakh nomadic movements with livestock—the central enquiry of this review—these sources generally agree that regular seasonal movements to graze livestock in mobile encampments were undertaken by the *aul*, a co-residential grouping formed around a core of patrilineally related kinsmen. Here we could think of a clan as an opportunistic aggregation "flexible and scaled at multiple levels. Contingent upon prevailing ecological conditions and constellations of external threats" (Schatz, 2004, p. 27), groups would form and fracture at different times. Thus the size of the migratory unit changed over time as households aggregated or dispersed according to season, pasture condition and labor requirements—with much larger aggregations in summer and smaller groups in winter (Masanov et al., 2001).

Still, having invoked the term, it behooves us to attempt some clarity in our application in this review, while remaining agnostic about the competing definitions. In the context of the social organization of Kazakh nomadic movements with livestock—the central enquiry of this review—these sources generally agree that regular seasonal movements to graze livestock in mobile encampments were undertaken by the *aul*, a co-residential grouping formed of members of a minimal segmentary patrilineage.

Intersecting and cross-cutting any discussion of kin-based nomadic livestock production systems—past and present—is the question of social stratification and class formations among Kazakh livestock-keepers. For the past, we only have written records of views expressed by Kazakh informants but written in other languages by geographers, administrators, ethnographers, and historians at different stages in the turbulent and often violent political-economic changes of what has become the modern state of Kazakhstan. Ultimately, the extent of class-like divisions between Kazakh groups in the historical period remains hazy. Comparison with other pastoral peoples (e.g., Bradburd, 1980; Sikana and Kerven, 1991; Borgerhoff Mulder et al., 2010; Murphy, 2015) indicates that frequent cycles of livestock accumulation followed by losses due to climate events, disease, conflict or conquest lead to fluctuations in the membership of a livestock wealth strata. As families and even clans entered or left a livestock wealth strata among the Kazakhs, there were associated oscillations for required labor and means of survival among differentiated livestock-keeping groups. Such instabilities in the distribution of means of production for the Kazakhs—livestock and labor—were and are still handled through patron-client relationships. The rigidity of these relationships may be shallow, over time, however.

KIN-BASED NOMADISM IN THE TSARIST PERIOD

Starting in the late 1700s, we have written material from the Russian imperial period on how the Kazakh nomads managed their livestock by tracking between ecological zones to seasonally-available grazing areas in order to avoid areas of temporary feed insufficiency, snow and/or cold, and to take advantage of natural forage surpluses in other areas (Khazanov, 1984; Olcott, 1995). The nomadic pastoralists accessed the pasture and water resources of the rangelands in extended family groups that moved and resided together in each season (Olcott, 1995; Aldashev and Guirkinger, 2017). Termed *aul*, these groups consisted of between 5 to 80 yurts (portable felt tents made from sheep wool) and had settled winter quarters made of durable materials (e.g., mud bricks and wood). The characteristics of the environment and the availability of water and pasture resources had an impact on the size of the camps because these factors determined the size of the herd that each *aul* possessed (Ohayon, 2004). A Kazakh nomadic camp in southwest Kazakhstan was photographed around 1860 (**Figure 2**).

The *aul* consisted of several conjugal families founded by direct male descendants of the same ancestor, hence a patrilineage (Ohayon, 2005). The *aul* was headed by elder men known as *aksakal* (literally "white beard"), who were charged with the protection of his pasturelands and people (Olcott, 1995). The elders would choose an individual termed *bii* to represent the clan in negotiations between other clans and *auls*, meet annually to decide on the routes for the season's migrations and allocate access to winter pastureland. The *biis* were expected to defend their groups' access to pastures, as well as arbitrate disputes (Martin, 2001). They were lesser nobles who represented lineage groups of Kazak nomads in negotiating annual migratory routes between clans, and also had a military role (Martin, 2001). A collection of groups "which might consist of 100 *auls* or more, migrated within an established geographic zone" (Olcott, 1995, p. 17).

This scale of nomadic movements managed through kin-centered social units started being curtailed when the northern pastures of the Kazakh nomadic pastoral tribes were effectively brought under the control of the Russian government, fortified and made available for settlement by Slavic peasants (Wendelken, 2000; Khodarkovsky, 2002). The colonial settlers' occupation in the 18th and 19th C of the fertile steppe used seasonally by Kazakh nomads became a "decisive destabilizing factor for the Kazakhs" (Kappeler, 2001, p. 189). As the extent of new Slavic peasant farming moved further south from the Russian borders, the nomads had to retreat with their livestock to the drier southern areas. "As far as the Russian government was concerned, the newly acquired lands were empty spaces belonging to no one…for the [Kazakh] nomads on the other hand, the same lands were indispensable pastures in common possession of the *ulus* [clans] or another aggregate nomadic unit" (Khodarkovsky, 2002, p. 216). When confronted with demands by the Russian frontier authorities to seek permission to use pastures and pay fees for crossing the rivers of the northern steppes, the Kazakhs responded with astonishment: "The grass and water belong to Heaven and why should we pay any fees?" (ibid.).

In the 19th C, numerous regional variations of nomadism and semi-nomadic pastoralism were recorded by Russian ethnographers and administrators in the territory that later became Kazakhstan (Federovich, 1973; Guirkinger and Aldashev, 2016; see **Figure 3**). The pastoralist mode of production varied according to three main factors: type of terrain (plains vs. mountains), climate regime (arid to wetter), water supplies (rivers and ground water), and associated pasture soils and vegetation. The plains-based nomadic economy depended on long distance migrations with grazing livestock, extending up to 1,000 km or more (Federovich, 1973) on a north-south axis throughout the year, traversing between the northern steppe, semi-desert, and desert in the south, where overwintering took place. Semi-nomadic groups also existed with permanent winter quarters. The mountain-centered livestock production system involved vertical transhumance, with settled winter bases in the valleys or semi-steppes around the mountains and transiting upland to alpine meadows for pasturing in the summer, with distances between summer and winter pastures often over 100 km (ibid.).

There were social distinctions according to a family's economic position in the community, in addition to an aristocratic genealogically-calculated hierarchy [see detailed discussion in Martin (2001), based on earlier sources]. The former aristocratic rulers (White Bones) were mostly co-opted or subjugated in the Tsarist period. By the late 1800s, Russian administration had eroded the large territorial and political units of the Kazakh upper levels of aristocracy, including the *bii* (Wendelken, 2000). At this time, the term *bii* seems to have become transcribed as *bai* [e.g., in Olcott, 1995]. *Bai* is a general Kazakh term for a rich person, who would own many livestock; possibly this conflation of terms may have occurred as the Russian administrators sought to co-opt the *bii* (Ohayon, 2005;

FIGURE 2 | Nomad migration, Syr Darya Oblast circa 1860 (now present-day Kazakhstan) Source: Turkestan Album, 1860s https://www.wdl.org/en/item/10987/#additional_subjects=Ethnographic$+$photographs&page=7. This photograph is from the ethnographical part of *Turkestan Album,* a comprehensive visual survey of Central Asia undertaken after imperial Russia assumed control of the region in the 1860s. Commissioned by General Konstantin Petrovich von Kaufman (1818–1882), the first governor-general of Russian Turkestan, the principal compiler was Russian Orientalist Aleksandr L. Kun, assisted by Nikolai V. Bogaevskii.

Sneath, 2007), who were elites in the Kazakh social structure. The position of *bais* (*bailar; kz)* as local leaders was strengthened as some Kazakh nomads began to settle into villages and Russian authorities empowered and paid the *bailar,* in a form of indirect rule, to collect taxes and maintain social order for the Russian administrators (Wendelken, 2000; Ohayon, 2005). As the *bii* became richer through Russian contact, a *bii* could be termed a rich man–a *bai*–as a consequence. As Russian settlement in the northern regions disrupted the Kazakh migratory routes, this lessened the larger-scale patronage and defensive ties which had previously existed between *auls* and higher-level social units, by breaking up the large territories of political power within a hierarchical social system (Martin, 2001). This increased Kazakhs' dependence upon their smaller *aul* groups, and a new social production system emerged based around the *aul obshchina (ru)* or "community," a partly-sedentarised community based on communal land use and herding of livestock.

Some of the need for nomadic movement was reduced when in the latter 19th C, the influx of Russian settlers and traders in the north created new markets for Kazakh livestock, particularly cattle, and in response, Kazakh pastoralists started to keep more cattle in addition to sheep in the northern steppe regions adjacent to the Slavic settlers (Olcott, 1995). But cattle, being less suited to long-distance migrations to avoid the worst of the frigid winters, needed more supplementary feed. Some intensification of pastoralism then occurred, when adoption of scythes, more efficient than the pre-existing hand sickles, permitted richer Kazakh nomads to harvest more hay to sustain their livestock,

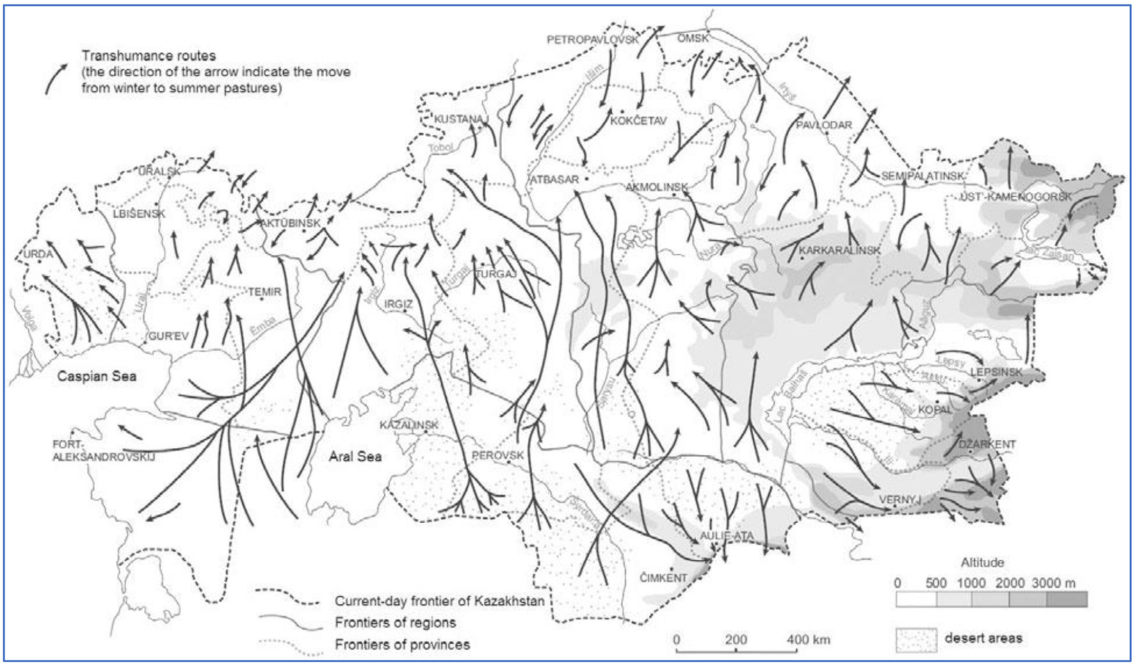

FIGURE 3 | Kazakh nomadic seasonal movements at the end of the 19th C. Source: Kerven (2004), Ferret (2014), based on (Federovich, 1973).

especially cattle, over the long bitter winters. One effect was to lessen the need for longer migrations to warmer locations and permit households to keep more animals (Kazakh Academy of Sciences, 1980; Matley, 1994b; Aldashev and Guirkinger, 2017). Thus, greater Kazakh sedentarization was possible and in some cases necessary, due to the expropriation of pastures by the Russian administraton for Slavic settlers (Kazakh Academy of Sciences, 1980). Wealthier Kazakhs even began to use hay mowers and hayland was one of the first types of agricultural land which richer Kazakh pastoralists sought to secure for exclusive use (ibid.).

Commercialization led to increasing economic differentiation among Kazakh pastoralists as livestock wealth became more concentrated into the hands of a few *bailar,* who had gained more recognized local level political power. "An increasing percentage of the total herd was held in an ever smaller number of hands" (Olcott, 1995, p. 99). However, even by the 1920s in northern Kazakhstan, the social and economic patronage obligations between richer and poorer related families in an *aul* meant that, as one elderly informant noted "rich people' does not mean one person" (Kerven, 2003). Different *auls* would be richer or poorer in livestock, with one richer and senior male in the lineage responsible for decisions on livestock management. The historical records of that period confirm this (Ohayon, 2005). By the end of the 19th C the number of yurts in an *aul* was reduced to 4 or 5 on average, while richer families, with larger herds and flocks, incorporated poorer people who carried out basic tasks in exchange for their upkeep in the *aul* encampment (Ohayon, 2004).

ENVIROMENTAL IMPACTS OF THE RUSSIAN COLONIAL PERIOD ON THE RANGELANDS

For the course of the Tsarist Russian period, there is scant evidence on environmental impacts of the changes to Kazakh mobile pastoralism wrought by the two major land use alterations: increasing colonization by Slavic peasant farmers which reduced nomadic access to the better-watered steppes, and the trend among Kazakh nomads to partially settle and grow feed and fodder crops. One historian's view was that "The nomadic livestock raising upon which was based the economy of desert region was so well-adapted to natural conditions that the landscape was very little modified, even in the sandy deserts which are very sensitive to the modification by man" (Federovich, 1973). Masanov (1990) likewise suggests that this system is one reason why environmental impact during this period was so minimal, as grazing pressure tracked vegetation availability without causing a negative impact on the environment.

Moreover, as livestock in the Eurasian rangelands were periodically decimated by ice and snow disasters (*dzhut* Kz), these non-equlibrium climatic conditions limited overall numbers and made serious degradation highly unlikely whilst livestock remained mobile (Sludskii, 1963; Robinson et al., 2003; Kerven, 2004). Severe cases of dzhut causing high stock mortality occurred every 10–12 years in the pre-Soviet period, according to Sludskii (1963) who noted that stock numbers would take around 10 years to recover from these events, leading to significant expansion and contraction in numbers. Herbivores in a non-equilibrium climate regime such as Kazakhstan's rangelands are less likely to threaten their overall feed supply since ecological carrying capacity is never reached, without supplementary feed sources (Ellis and Lee, 2003). This situation was to be completely upturned from the 1950s onwards, as we shall discuss later.

COMPRESSION AND COLLECTIVIZATION OF THE NOMADS: EARLY 20THC

Throughout the latter period of Tsarist Russian administration of Kazakhstan's northern regions, this land "had long been viewed as a source of new farms. In the period 1896–1916 it received over one million settler families from European Russia" (Olcott, 1981, p. 124), mainly to the better-watered steppe region of rich grassland which had been the summer grazing area of Kazakh nomads. But the temporary nomadic use of the steppes was "seen as a hindrance to the expansion of grain-growing, as the animals grazed on hundreds of thousands of acres of potential farmland. The colonial settlement policy caused great hardships for the Kazakhs as it severely restricted the access to pasturage.... When the Bolsheviks came to power they made the settlement of the Kazakh nomads an avowed goal" (ibid.).

However, the Bolshevik revolution in 1917 did not immediately change the situation of the nomads and semi-nomads in the Russian-controlled regions of Kazakhstan, as Russian peasants continued to settle further south into the territory (Allworth, 1989). The area of modern Kazakhstan was formally incorporated into the new Soviet Union in 1924. The Russian census of 1926 (just before collectivisation) found that summer migration concerned 65% of the Kazakh population and long distance multi-season migrations only 7–8% (Ohayon, 2004). The frequency of hay making, a propensity to hold cattle and the proportion of entirely sedentary households all increased in this early colonial period—by 1910 it was estimated that only between 2 and 10% of Kazakh houseolds were sedentary (Kazakh Academy of Sciences, 1980).

Some Russian administrators had argued that the nomadic pastoral way of life was a form of environmental adaptation, and that as long as the environment did not change, nomadic pastoralism would continue to exist (Werner, 1997, citing Russian sources). In the 1930s, however, Soviet academics claimed that nomadic societies had developed class relations before the Bolshevik revolution, tribal leaders in nomadic pastoral societies were feudal rich people—*bailar*–and that nomadism was not efficiently productive (ibid.).

Fluidity of socio-economic strata is mentioned in (Hudson, 1938) writings at a particularly dreadful time in modern Kazakh history (p. 58). "The poor or middle-class Kazak was always in a precarious situation because the loss of his few cattle placed him in complete subjection to the wealthy owners of large herds." Radlov, writing in 1893, observed that "a Kazak who had lost his animals through drought or a severe winter had no resource but to hire himself out as a worker" (Hudson, 1938, p. 58). These herders did not receive a salary but only food. Such people were referred to as clients of a rich man, and the clients were "his own more or less distant relatives." Another Russian commentor, Grodekov noted in 1889 that "in strong tribes, the poor people migrate with the rich, remaining always with their group for the sake of the protection afforded by the rich, paying for it with labor" (cited in Hudson, 1938, p. 58).

Under the new Communist government, collective farms termed *kolkhozy* were started from 1924, as communes were formed around the semi-settled villages governed by the *bailar* to control livestock, migratory movements, and water points. Then began the brutal programme of enforced nomadic settlement and expropriation of livestock in "the drive for collectivization" (Olcott, 1995). In 1928, under Stalin, livestock began to be confiscated from Kazakh families and placed into *kolkhozy*. This was the period known as "Stalin's Terror" and the great famine ensued from 1931 to 1934 in Kazakhstan (Kindler, 2018; Thomas, 2018).

From 1930, the main means of Kazakh collectivization was "dekulakization," the removal from villages of allegedly "well-off" exploitative peasants—kulaks–and others who opposed too openly the program of collectivization, as officials considered dekulakization necessary to enable collective farms to work (Conquest, 1986, p. 193). Among those accused of being kulaks were some of the Kazakh *bailar* who had accumulated livestock wealth under the previous Russian administrative regime, and were then denounced by settled ex-nomads (Thomas, 2018).

There were enormous consequences for Kazakh pastoralists of the radical methods for collectivizing pastoral regions and enforced sedentarization (Lorimer, 1946). Among the impacts was lack of available fodder for winter in the collective farms, as livestock were not taken to winter pastures (Davies and Wheatcroft, 2004). There was a catastrophic crash in livestock numbers in the early 1930s as a consequence (see **Figure 4**).

COLLECTIVIZED INDUSTRIAL NOMADISM: MOBILE LIVESTOCK HUSBANDRY AGAIN ENCOURAGED

During the attempt to formally sedentarise Kazakh nomads from the 1920s, the loss of nomadic mobility meant the collapse of social relationships in practicing the seasonal migrations with livestock (Kindler, 2018). But by the mid 1930s, Soviet policymakers de-emphasized sedentism after witnessing the catastrophic effects of initial enforced reduction in livestock mobility and restriction to the collective farms, as "Nomadic practices, they discovered, allowed large-scale livestock rearing in the steppe. The Bolsheviks began to rely on what they formerly rejected" (ibid).

While historians have concentrated their attention on the most dramatic disruptions to Kazakh nomadic husbandry over the last 100 years—forced collectivization and the famine that resulted in the early 1930s–after the middle of the last century, from the early 1940s to the late 1980s, there was a re-emergence of long-distance nomadic livestock management (Alimaev and Behnke, 2008; Robinson et al., 2016). At the beginning of World War II, an official USSR decree re-instituted migratory pasture use, "to organize distant pasture management...establish

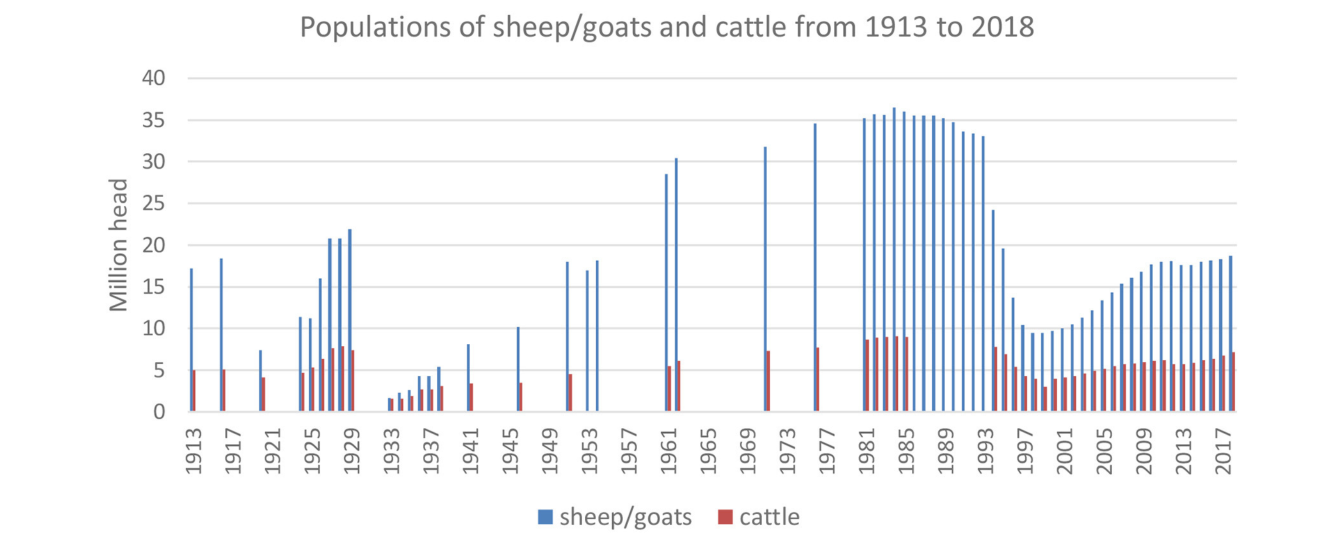

FIGURE 4 | Changing numbers of main livestock species in Kazakhstan over a century. Sources: Olcott (1981), Allworth (1989), Channon and Channon (1990), FAOSTAT (2020).

livestock movement tracks for accessing distant pastures, ... Organize stopping points along these routes ...provided with water and ...fodder" etc. (cited in Alimaev and Behnke, 2008, p. 178). Several reasons led to this volte-face; the Kazakh nomads had been largely pacified after the brutal collectivisation effort of the 1930s and earlier repression of uprisings at the turn of the 20thC (Olcott, 1995). Secondly, technical appraisals of the costs and returns to sedentary livestock management in the collective farms concluded that it was more efficient to allow animals to graze natural pastures when and where possible, thereby increasing livestock output at less cost (Zalsman, 1948, cited in Alimaev and Behnke, 2008). Thirdly, Soviet scientists undertook close analyses to gain a clearer appreciation of the Kazakh nomads' knowledge of seasonal pasture usages and livestock responses. Lastly, engineering and scientific advances under the Soviets generated new technology: to supply stock water; to irrigate feed crops; to develop new livestock breeds; to precisely assess natural pasture productivity; to calculate stocking rates and finally to dictate seasonal stock movement schedules aligned to optimal pasture nutritive values at different times and places (Asanov and Alimaev, 1990; Zhambakin, 1995). What had been created was in essence, a form of industrialized nomadism, in which the latest modern technical assets were coupled with ancient pastoralist skills, to adapt to and exploit the variable environment of Kazakhstan's pasture wealth. This was a true marriage between Soviet obsession with modernization—electrification and heavy machinery—and Kazakh nomadic practice, sanctioned by Soviet scientists and driven by wartime pragmatism in WW2.

As early as 1935, for example, the practice of *otgon (ru.)* (or "remotely driven") pastoralism was permitted within the collective farm system (Werner, 1997). Although *otgon* pastoralism entailed the seasonal migration of livestock to different pastures beyond the collective farm boundary territories, the national authorities organized this very differently from the previous clan-based nomadic or transhumant pastoralism when a larger kinship group (the *aul)* migrated seasonally. In the newly-devised state livestock farms, small groups of employed shepherd families migrated to designated sequence of pastures with the state-owned flocks and herds.

Replacing the former "clan"-based livestock production system demanded new technical inputs, while traditional nomadic herding knowledge had to be activated through collective wage labor. The destruction of the old nomadic social order achieved in the earlier part of the 20th C left Kazakh families atomized, unable to manage large flocks or herds without extended kin. The upheavals of the 1930s had dislocated many Kazakh clan associations, as many families had died or emigrated to Persia or Chinese Turkestan; amongst those remaining in Kazakhstan, the collectivization process, and dekulakization had pulled larger kinship-oriented groups apart and segregated them into isolated settlements scattered across the rangelands. The scale of mobile livestock management was not feasible by individual families.

By the time USSR policy in the 1940s dictated that livestock management should return to more pasture-based seasonally-mobile nomadism, the social keystone for nomadic movement—the broader labor unit of an *aul* based on a patrilineage–had vanished. In its place was designed the brigade system, in which all collective farm labor was formally divided into group specializations such as: agricultural machinery (e.g., harvesters, tractors, trucks); veterinary; engineers for wells, irrigation systems and dams; accountants; and crucially, shepherding groups in charge of each livestock species and reproductive categories such as mating, lambing, calving etc. Collective farm families in these newly-settled villages received a salary plus housing, and schooling and other social services including shops, medical facilities and pensions were provided. These new large state-managed farms gave rise to a new rural elite based on administrative control–the directors and technical staff of collective farms–and formally-educated professional status, rather than an elite based on personal livestock wealth and social prestige, as had been held by the *bailar*, who had either fled or been liquidated (Olcott, 1981).

The role of Kazakh women in livestock farming during the Soviet era was problematic. Women's emancipation and higher education was emphasized in the Communist ideology and some village women became teachers, accountants, nurses etc. At the same time, female fertility was officially promoted, e.g., with the "Order of Maternal Glory" awards for having many children. The state's provision of childcare and other social services was a buffer, but it appears that women did not abandon their pre-Soviet roles regarding daily tasks tending their family's own small flocks of animals that were permitted in the Soviet era (McGuire, 2017).

As the Kazakhstan national flock grew in the new collective farms, pressure mounted from central planners in Moscow to continually increase livestock output—herd numbers and amount of meat, wool and dairy products–to supply other parts of the Soviet Union with meat and wool (Asanov and Alimaev, 1990). This was achieved by intensification through cultivating more fodder crops with irrigation, and building new state livestock farms in more arid and less productive rangelands (Asanov and Alimaev, 1990; Gilmanov, 1996). The shift was completed by the mid 1960s, as large livestock farming settlements, complete with electricity, high schools, hospitals, and even theaters, were established in the semi-desert, while long-distance livestock movement covering many hundreds of kilometers was still undertaken using the brigade system. Livestock populations steadily grew from this point up until the crash after 1991 (see **Figure 4**).

ENVIRONMENTAL IMPACTS OF CHANGES IN LIVESTOCK MANAGEMENT DURING THE SOVIET ERA

The Soviet system of planned migrations was explicitly based on estimations of vegetation productivity, edibility and carrying capacity—which were mapped in great detail across Kazakhstan. Movements, grazing periods and supplementary feeding were planned with the dual objectives of maximizing production within environmental limits. However, in the 1960s the state attempted to intensify production in arid and semi-arid areas by increasing stocking numbers, extensive well-construction and reducing long-distance mobility, and it was at this point that the environmental impact began to worsen (Asanov and Alimaev, 1990).

The creation of 155 specialized sheep-raising *sovkhozes* on state reserve land, each with a stock of 50,000–60,000 sheep, blocked northwards migrations and forced state farms sited further south to spend more time grazing livestock on what had previously been only used as autumn and spring pastures. The vegetation was unable to develop and seed, reducing yields to almost half of what is ecologically possible and led to soil degradation across large areas (Zonov, 1974; Asanov and Alimaev, 1990; Zhambakin, 1995). These problems were compounded by the plowing up of the best summer pastures in the 1950s, which increased reliance on the semi-arid pastures. As animal numbers expanded, herding labor and feed supplies were not the constraint to herd growth, but the natural pasture zones became over-used as seasonal pasture use "came under increasing pressure as all available grazing niches were occupied" (Alimaev and Behnke, 2008, p. 167).

Land degradation toward the end of the Soviet period was mapped according to anthropogenic desertification (Babaev and Orlovsky, 1985), but covering only arid and semi-arid regions of Kazakhstan. By the end of the Soviet period almost 60% of the area of arid and semi-arid Kazakhstan was affected (Kharin and Kiril'tseva, 1988; Babaeva, 1999), principally degradation of vegetation cover covering 44% of arid lands (Kharin et al., 1986). These authors blamed livestock production as the chief cause. But not all the area was severely affected; for example moderate degradation "involves the presence of more or less stable associations that have been productive for long periods but still include weed species" (Kharin et al., 1986, p. 63). Most moderately and severely degraded areas were to be found on sandy soil and livestock wintering areas. Dzhanpeisov et al. (1990) and Babaev and Kharin (1991) note that pastures on sandy soil, such as the Moiynkum desert, are often severely degraded due to density of infrastructure such as cattle trails, winter camps, watering places, and shearing and dipping stations, created by the large-scale state livestock farms since the 1940s.

DESTRUCTION OF COLLECTIVE LIVESTOCK FARMS AND RISE OF PRIVATE OWNERSHIP AFTER THE USSR

The complex and costly apparatus of the state livestock farms rapidly began to disintegrate after the end of the USSR in 1991. By the mid 1990s, loss of the USSR-wide markets, currency devaluation, and farm debts forced most livestock *sovkhoz* in Kazakhstan into bankruptcy; farm assets including livestock were officially privatized (World Bank, 1993). One of the cornerstones of the *sovkhoz* system of livestock production had been the provision of high-quality winter fodder and feed supplements, sometimes imported from as far away as Ukraine. Intensive winter feeding had allowed steady growth of the livestock population (see **Figure 4**) to meet the central planning orders, but to the point where some ecological zones were experiencing pasture degradation, as noted above (Asanov et al., 1992; Ellis and Lee, 2003). This was the setting for the complete transformation of the former production and land use system.

The dismantling of state and collective farms was largely completed by 2000. This process and its evolving effects were documented in a series of field research projects in south central Kazakhstan between 1997 to 2015, summarized here.

Privatization of the state farms was implemented hurriedly under duress, by state officials in shock and with incentives provided by the Western financial agencies i.e., World Bank, International Bank for Reconstruction and Development, and International Monetary Fund (Spoor and Visser, 2001). Not surprisingly, privatization had deep and very damaging structural impacts. Nearly all the physical inputs necessary for seasonal livestock movement disappeared—heavy transport, fuel, housing etc. (Behnke, 2003; Robinson and Milner-Gulland, 2003a; Kerven et al., 2004). The state no longer provided winter fodder for animals, while irrigated or rainfed land previously used for fodder crops was converted to higher-priority food and cash crops. State farm workers lost their jobs, wages and social security benefits. Individual rural families had to work out how they were going to raise livestock without any external assistance in the form of government inputs, subsidies, or technical advice from professionals. Most ex-farm employees were in a state of shock and sought only to survive, mainly by bartering and slaughtering whatever livestock they had managed to obtain from their former state farm employers.

By the time the USSR ended, there was surplus rural labor required for livestock production (Ellman, 1988; Lerman et al., 2002). In Kazakhstan, as livestock numbers crashed due to the end of subsidies and economic chaos (see **Figure 4**) there was a rural exodus to seek work and incomes in urban areas, as agricultural households experienced greater poverty (Behnke, 2003; Spoor, 2007). Remaining behind were smaller family units, as women had fewer children, rural child mortality rates increased (UNICEF, 2006) and adult children increasingly left the villages for higher education or work in towns (Pomfret, 2003; McGuire, 2013), rejecting the conditions of village work with livestock. The rural demographic pattern changed to an older age structure, leaving a shortage of younger family labor for the strenuous work of livestock production. In the absence of sufficient family labor, household flocks had to be entrusted to shared local labor or casual itinerant laborers, who might have little previous experience of herding. Many livestock were simply slaughtered for local consumption or sold to quickly-developing private markets for barter or cash to pay debts and buy food (Kerven, 2003; Kerven et al., 2004). New informal markets were flooded with supplies of livestock, causing prices to collapse which obliged people to sell still more livestock to buy food and other necessities. The few remaining livestock formed tiny flocks for newly-impoverished villagers who lacked other resources or income (Kerven et al., 2004). Traveling with livestock in mobile flocks became much more risky and costly for most rural families, due to greatly diminished economies of scale.

Concomitant with this reversal of labor conditions after 1991, the capital-heavy technology supplied and maintained by USSR subsidies for state farm use was abandoned, wrecked, appropriated, or melted down and sold to Chinese buyers. Irrigation pipes were smashed and not repaired. Mechanical pumps were stolen or effectively privatized on former communally-used wells when pasture land was allowed to be privately leased (Behnke, 2003; Kerven et al., 2004). Heavy machinery such as harvesters for fodder and trucks for livestock transport was similarly taken out of communal farm and transferred to private property. Only a few individuals perceived the opportunity to garner these valuable capital assets in the prevailing chaos. These individuals were typically members of the Soviet farm professional elite—with tertiary education as veterinarians, accountants, agricultural engineers or animal husbandry specialists–who had managed the state farms and largely inherited the assets of the defunct farms (Behnke, 2003). In the process of dismantling state farms, members of this elite were in a position to appropriate much of these farms' capital equipment and infrastructure. Through their acquisition of key inputs, the elites were able to achieve the economy of scale needed for mobile livestock management as "Lumpiness or fixity of assets is one of the main factors contributing to economies of scale" (Lerman et al., 2002, p. 46).

NOT ALL PEOPLE ARE EQUAL: BESHBARMAK "FIVE FINGERS ARE NOT EQUAL."

In a remote desert garage on the trunk road from Almaty to Moscow, 7 years after the collapse of the USSR in 1991, a former state-employed mechanic had accumulated 100 cattle, 200 sheep, 40 horses, and 15 pigs. He asserted:

> "My grandfather was a *bai,* a very wealthy man. In 1928 their livestock were taken by the government. These days, now, people are learning. In the past, Kazakhs could maintain their animals by moving and never used to be commercial… Firstly, pastoralists need land, private land—need 100,000 ha for one family. I would not want to fence this land, as before people divided up the land without fencing. There would be enough [range] land for those who want. On this land I would bring workers who would have jobs and I would not have to sell my wool to Chinese traders at such a cheap price. No one should prevent me from working as I want on the land. My grandfather had a lot of private land and he knew what to do with this land. *Beshbarmak* "five fingers are not equal."[2] (Kerven et al., 1996, field notes).

Farm privatization was allowed to proceed with little or no intervention from the state, leading to large-scale inequities in the distribution of state material, landed resources and livestock (Behnke, 2003; Dudwick et al., 2005; Robinson et al., 2012). The maldistribution of former collective farm assets meant the appearance of a new minority group of large-scale livestock owners who had distinctive social and economic attributes initially noted in a two-year survey of sheep-owning households in the rangelands of south-central Kazakhstan (Kerven et al., 2004, 2006; Milner-Gulland et al., 2006). Successive government policies and laws allowed these large-scale livestock owners to register leasehold title over former state farm pasture land containing key resources such as water points, barns, hayland or winter houses in the seasonal grazing areas. They had bought or appropriated discarded heavy transport Soviet vehicles that allow them to support their animals and hired herders in remote grazing areas and to take animals to distant urban markets for better prices. As the national economy was bolstered after 2000 by oil and gas extraction, growing urban incomes increased demand

[2]Literally "5 fingers" referring to the national celebratory meat dish of Kazakhs and Central Asians, traditionally eaten by hand using 5 fingers.

for meat (Pomfret, 2009), which meant that raising livestock for a commercial market became even more attractive for those who could seize the opportunities (Kerven, 2003). Being able to profit from these markets led to further accumulation of livestock and capital investment into their livestock enterprises. They quickly developed a commercial rather than subsistence approach to livestock marketing, selling fattened male adult animals in urban markets at seasons when prices were highest (Kerven, 2003). Livestock wealth has tended to accrue largely to these owners, widening the disparity with flock and herd sizes of the majority of owners (Kerven et al., 2016a).

The large-scale owners typically have certain social characteristics in addition to having initially acquired the material assets needed for managing large flocks (Kerven et al., 2016a). They deploy extended kinship networks in both their village and cities to combine access to crucial resources of rural infrastructure (barns, houses, wells), arable or hay land, family labor for flock management and financial credit. The large-scale livestock owning farms are usually multi-generation patrilineal family units, consisting of a father and several older sons, or several brothers and male cousins working together. Similar patterns are recorded by McGuire (2013, p. 35), who remarks on the resemblance to pre-Soviet interdependencies between shepherding labor, livestock numbers and social differentiation: "Families have surmounted the challenges posed by a lack of sheep or a need for sheep husbandry by fashioning collectives that stitch together the land, labor, and flocks of multiple disparate households. Extended networks of kin band together to create flocks, and poor households ensure access to land–and perhaps their own future flocks–by trading labor for sustenance and a share of the flock's live offspring."

The big sheep owners initially in the early 2000s often hired herders, who were indigent (homeless) non-ethnic citizens or impoverished people from neighboring Kyrgyzstan or Uzbekistan willing to work in remote locations for their keep only, in the early 2000s. But a decade later, as being a big livestock farmer became more lucrative, sons or brothers of the bigger flock owners were assigned to supervise the workers while the livestock owners–heads of their families–based themselves in comfortable village homes or even in provincial towns and cities. The owners make livestock management decisions as semi-absentees by visiting their flocks regularly to check up and bring supplies.

Shepherding remains a gendered task as in the recorded past, since men accompany the sheep and goats, on horseback if possible, throughout the grazing day due to predators (jackals and wolves). Horses, cattle, and camels can be left to graze unaccompanied nearby villages or camps, but must be led by men out and back from pastures. Women and older children may be responsible for putting livestock into barns, giving them fodder, and tending young animals, as well as milking cows and horses, and sometimes goats.

With regards to changes in gender roles in managing livestock, there is remarkably little ethnographic or quantitative material. Efficient management of private large flocks requires shepherding labor to undertake seasonal movements, and this requires feeding the shepherds. One recent analysis in southern Kazakhstan (McGuire, 2017) notes the social tension arising from "the necessity of women's domestic labor to the operation of a herding camp" creating new economic ties between households, through marriages intended to support shepherding (McGuire, 2017, p. 121).

The amalgamation of rising prices for meat, new sources of investment capital, new government policies after 2003 all "stimulated the revival of livestock farming" (Pomfret, 2009, p. 35), and encouraged private leasing of pastureland by bigger stock owners. There is a rising wealthy class of livestock producer—the new *bailar*. Their most significant difference with smaller livestock owners' method of production is their return of long-distance migrations to seasonal pastures (Kerven et al., 2006, 2016a,b). These men explicitly refer to the past, in planning their future.

The new big flock owners are not apologetic. They assert that they are either restoring an old order of control exercised by their ancestors, when they can claim descent from *bailar*, or to be embracing the new market economy which is encouraged by the national government. In contrast to the social position of *bailar* prior to the repression of the 1930s, the new livestock elite do not consider that they have any social, political or economic obligations toward the wider communities within which they reside. These new *bailar* are modern men who equate themselves to Australian or American ranchers. They seek imported high-yielding exotic breeds of livestock, market their animals very efficiently by fattening before selling and waiting to sell in seasons when prices are highest, invest in new technology and refer to their grazing outposts as *"fazenda,"* (ranch in Portuguese) learned from watching a popular TV soap opera about ranchers in Brazil (Kerven et al., 2016a). The new big livestock owners are, in effect, open-range ranchers.

PASSIVE AND ACTIVE IMPACTS OF GOVERNMENT PROGRAMMES

For nearly a decade after independence in 1991, the state paid little attention to the livestock sector on the rangelands, being preoccupied with profiting from development of the enormous reserves of oil and gas within these rangelands (Pomfret, 2009). The formal role of the new local and national government after independence in 1991 was limited to new pastureland tenure regulations (Robinson et al., 2012), much of which were misinterpreted or circumvented by livestock owners in practice (Behnke, 2003; Kerven et al., 2006). The livestock sector therefore evolved in an unregulated vacuum of central power and under the control of local privileged elites, survivors from the Soviet period in the chaotic early transition period.

In the last few years, the Kazakh government has issued laws and programmes that appear to support large-scale livestock owners and ignore the mass of small-scale owners (World Bank, 2019a; Robinson, 2020). A vast subsidy programme between 2017 and 2021, currently over 90 million USD, created subsidies for registered farmers but only the largest farmers who meet herd size and land area conditionalities received these subsidies. The subsidy funds were principally intended to promote intensification, through improved feeding, animal housing, using imported pedigree stock, and ranching-style management (Robinson, 2020). There are approximately 200,000 registered farms and a very small number of quasi-government livestock enterprises, mainly specialized breed farms (ibid.). In comparison, there are 1.6 million rural households, who collectively own nearly two thirds of the nation's livestock, but whom have not benefitted from the government subsidies. These small-scale household farmers have on average 2 cattle and 7 sheep or goats, while the mean for the 200,000 registered private farms is 11 cattle and 34 small stock (ibid.). The size of livestock holdings is highly stratified between and within these official categories of farms, as illustrated in **Figures 5A,B**, from two case studies carried out from 2011 to 2015 in the Moiynkum semi-arid region of south central Kazakhstan (see Kerven et al., 2016b; Robinson et al., 2017) and three wetter districts of Almaty Province in 2018 (Robinson, 2020). Nationally, the village households who comprise nearly 90% of all livestock owning units, have much smaller flocks and herds than the small group of private registered farmers and enterprises (**Figures 6A,B**).

A recent World Bank (2018) review of Kazakhstan's agricultural programme recommends shifting subsidies to promote productivity, growth, and environmental sustainability, explicitly recognizing that extensive livestock management can be more environmentally sustainable than greater reliance on cultivated fodder crops and reduced natural grazing. New subsidy packages and messages are currently being planned by the World Bank together with the Kazakh government, in the Kazakhstan Sustainable Livestock Development Project, 2020–2024 (World Bank, 2019b). Apparently, the Kazakh government is shifting the focus of state support to small and medium farmers—but only cattle farmers–and away from the sole focus on large agri-enterprises. The new subsidy project is targeting medium farmers having 10–50 head of cattle, as well as large registered farmers and enterprises with up to several thousand head of cattle.

There are contradictory signals from the government and external agencies. On the one hand, generous subsidy and advisory packages are targeted at the larger herd and flock owners, who may already be practicing seasonal livestock mobility, while on the other hand, programmes are promoting intensification of livestock feeding by growing more feed crops. Although most of these government subsidies have promoted sedentary farming and intensification, funds targeted for water point and winter house rehabilitation (Robinson, 2020) also indicates a policy to promote distant pasture use. Nevertheless, at present the indications are that only those registered farmers with larger flocks or herds are entitled to benefit from these government promotions.

There is yet very little practical support to the preponderance of Kazakhstan's livestock owners, who individually own only a few animals and therefore cannot access distant pastures as their livestock holdings are too small.

Pastoral Scale and Livestock Mobility

Considering the past on the Kazakh rangelands gives us a window for speculating about some potential trends for the near future. Will pastoral mobility decline further; will more pastoralists return to mobile livestock management; what are the attractions and disincentives for these choices; and what could be the most effective forms of grazing land management for the environment and for human welfare?

The Kazakh government considers the mostly sedentary village-based livestock farmers to be economically unviable and their animals a threat to the grazing land around villages, which has become overgrazed since the end of the USSR (Ellis and Lee, 2003; Alimaev et al., 2008; Dara et al., 2020). The circum-village overgrazing is due to small-scale livestock owners being usually unable to seasonally migrate to distant pastures—either hundreds of km across the desert and steppe plains, or vertically up steep mountain tracks–due to the cost of transport, unavailability of labor, badly maintained roads, and bridges etc. (Kerven et al., 2004, 2006, 2008, 2016b; Hauck et al., 2016; Ferret, 2018; Robinson, 2020). Nevertheless, in better-favored locations nearer to cities with high demand for livestock products of meat and dairy, it has been economically viable for a minority of small-scale livestock owners to continue vertical transhumance from valleys and plains in winter to high summer mountain pastures in summer, using spring and autumn pastures in the foothills, with several hybrid forms of social organization (McGuire, 2013; Hauck et al., 2016; Ferret, 2018). Those small livestock owners who send their animals away to graze for the summer are likely to do so by grouping animals with those of larger livestock owners while wealthier families with more livestock hire their own private shepherds to tend their flock for the summer mountain period.

Although the majority of Kazakhstan's livestock are owned by small-scale farmers, they can only legally access 12% of pasture area, which is immediately around villages, compared to the minority of registered farms which have so far leased double this amount of pasture (Robinson, 2020). A further half of the nation's pastureland, much of which is theoretically available for lease, still remains under direct central state control. This state land can be used for grazing, either informally or with official permits. Nevertheless, this state pastureland is typically quite remote from settled villages, which reduces the chance for small-scale livestock owners to seasonally move their livestock for grazing away from the villages. Meanwhile, small-scale livestock owners are increasingly excluded from the more productive pastures which being more distant, also have lower grazing pressure and accessible ground water, and have already been privatized either de facto or de jure (Kerven et al., 2016a,b; Robinson et al., 2017). After decades of stasis, long distance migration and short distance transhumance are re-appearing, but only for the larger flocks. Larger herd owners in the post-Soviet era can take advantage of economies of scale by reducing their production costs per livestock head taken on long-distance migrations (Robinson and Milner-Gulland, 2003a; Kerven et al., 2004, 2006). At the same time, formerly mobile pastoralists have become mainly

FIGURE 5 | Current livestock distributions by households and registered private farms, from two case studies in southeastern Kazakhstan 2012 and 2018. **(A)** Households (unregistered). **(B)** Registered private farms. Sources: For Raiymbek case study, "Revitalizing animal husbandry in Central Asia: A five- country analysis, funded by the German Federal Ministry of Education and Research" (Robinson, 2020). For Moiynkum case study, data from "Mobility versus Exclusion: Limits to Ideal Free Distributions in Pastoralist Systems," Leverhulme Trust to Imperial College London 2011–2014 (Kerven et al., 2016b; Robinson et al., 2017).

sedentarised, by being unable to afford seasonal movement and being effectively excluded from government subsidy and credit programmes or through family choices of alternative livelihoods (ibid.).

A Century of Change in Kazakhstan's Livestock Holdings

Figure 7A indicates that a century ago, Kazakh livestock-owning units had much higher mean numbers of livestock—nearly 4 times more sheep, twice as many cattle, 5 times more goats, 7 times more horses and 20 times more camels, compared to the mean of private farms and households owning livestock at the present. There are now nearly the same national number of sheep and cattle as recorded in 1913, but these are currently distributed between 1.9 million livestock-owning units compared to less than half a million a 100 years ago (Kazakh Academy of Sciences, 1980; Kazakhstan National Statistical Agency, 2018). The national proportions of sheep and cattle are remarkably similar in the past and present, as shown in **Figure 7B** –but there are now fewer horses and camels previously required for transport.

Environmental Impacts of Livestock Management in the Post-soviet Period

There are undoubtedly environmental consequences of these recent recorded changes in land use and livestock management. If the rangelands of Kazakhstan are partly the product of livestock grazing over millennia, can effects be discerned of the most recent changes happening in the last decades? What changes can be anticipated in the near future?

Several kinds of environmental changes in the current and former grazed rangelands have been quite closely monitored since the collapse of state-managed livestock and crop farming in the early 1990s. Firstly, field analyses have been carried out on the several different types of vegetation successions occurring

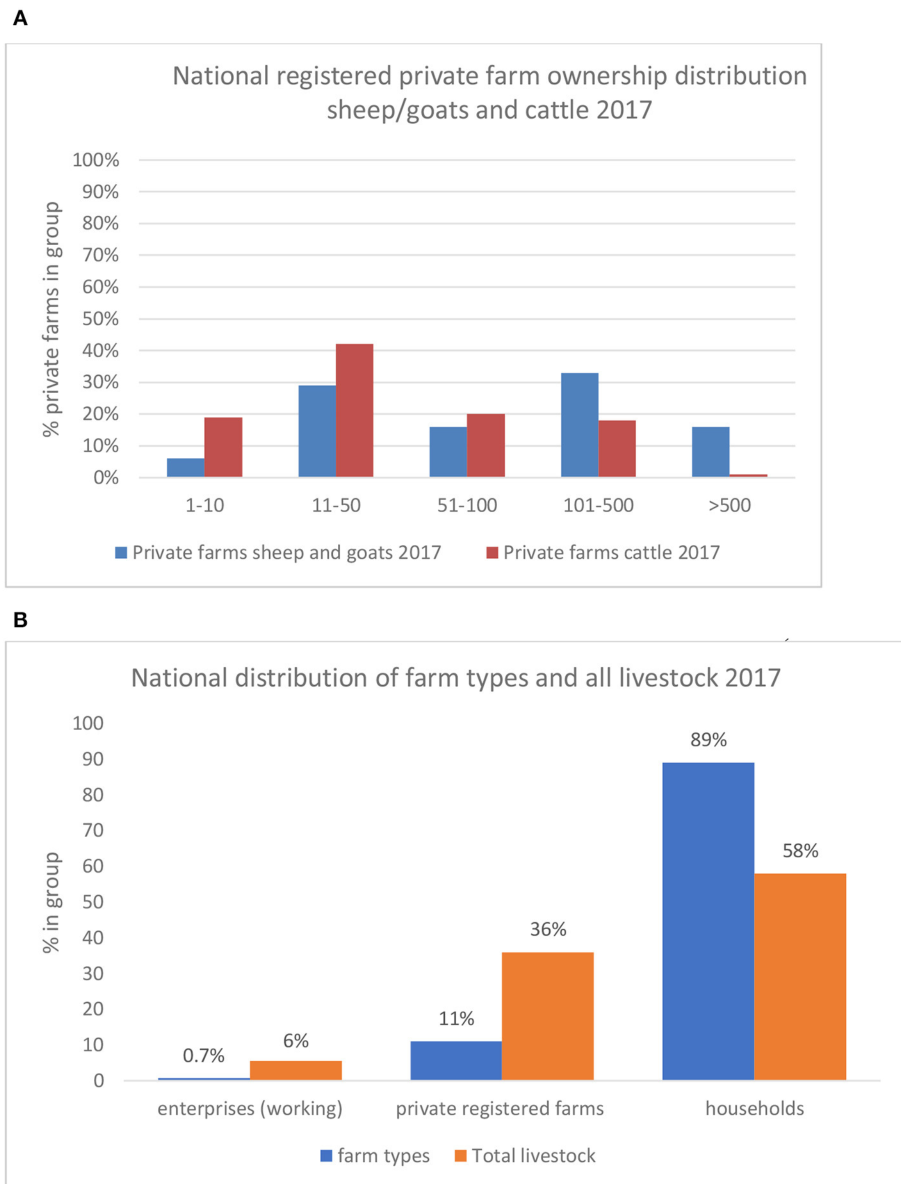

FIGURE 6 | National livestock ownership distribution 2017. **(A)** Registered private farms sheep/goats and cattle. Source: Kazakh National Statistical Agency 2018. **(B)** All livestock (sheep, goats, cattle, horses, and camels) by farm type 2017.

with the rapid and radical changes in land use since 1991. Land on large state farms which was cropped for many decades before the 1990s has been abandoned and is returning to rangeland. In another process, land that was formerly grazed for many decades is now only being lightly grazed or not at all. Secondly, there have been investigations of how land use changes have affected carbon sequestration in plants and soil, mainly due to abandonment of cropping in the former Virgin Lands region of northern Kazakhstan and some return of livestock grazing (Perez-Quezada et al., 2010; Kurganova et al., 2015; Schierhorn et al., 2019). Thirdly, there are studies on the biodiversity implications of the radically altered livestock grazing pressure patterns and crop cessation (Kamp et al., 2009, 2011, 2015, 2016). Together, these changes over the last three decades point to the substantial effects of different livestock grazing intensities on the ecology and sustainability of the Kazakh rangelands for the future.

Rangeland Vegetation Transformations

As rainfed cropping sharply declined with the absence of state support after the end of the USSR, by 2000 about 40% of arable land in Kazakhstan had been withdrawn from cropping

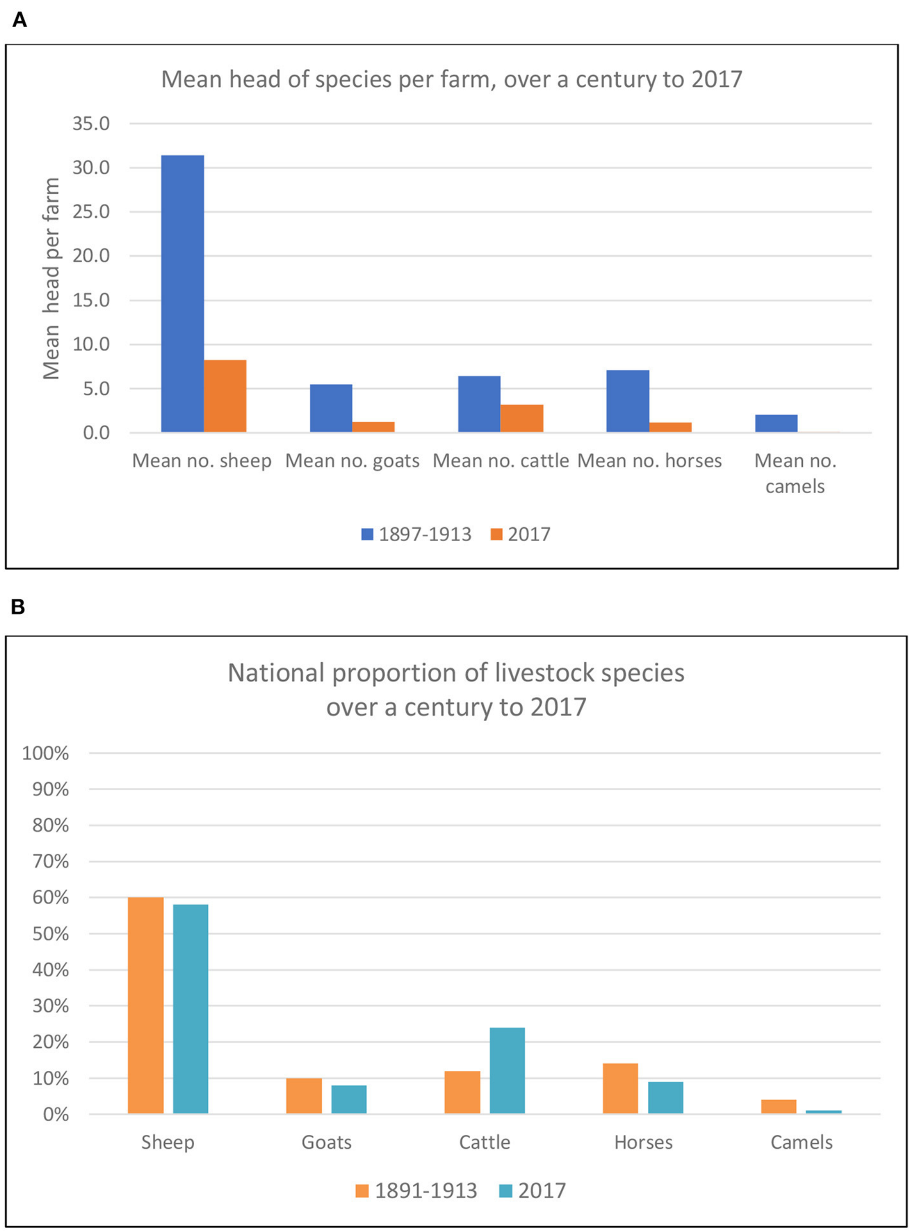

FIGURE 7 | A century of change in Kazakhstan's livestock holdings. **(A)** Changes in livestock holdings per farm in Kazakhstan. Total number of households in 1897/1913 was 582,587 (nearly all rural). In 2017 total private registered farms and households (excluding large commercial enterprises) was 1,832,248. **(B)** Changes in the species of livestock kept in Kazakhstan. Sources: (Kazakh Academy of Sciences, 1980; Kazakhstan National Statistical Agency, 2018).

over two decades (Kamp et al., 2011; Dara et al., 2020). Some 14.1 Mha of abandoned crop land remains uncultivated (Schierhorn et al., 2019). Over the same period, as has been discussed here, livestock numbers crashed, most of the remaining livestock could not be taken to remote pastures, and instead had to be grazed around villages (Behnke, 2003; Robinson and Milner-Gulland, 2003b; Robinson et al., 2016). This second process has led to a mosaic of heavily grazed and ungrazed or lightly grazed rangeland zones, with consequent ecological impacts.

One detailed study (Brinkert et al., 2016) examined the changes in vegetation diversity resulting from these combined processes of spontaneous succession of the abandoned crop land and the loss by the late 20th C of both domestic and wild ungulate grazers, the latter mainly *Saiga tatarica* antelope. The study compared plant succession and soil conditions in grazed and ungrazed abandoned crop fields and "near-natural" steppe, and found that grazing greatly hastened the return of these abandoned lands to steppe-type vegetation. The authors theorized that due to the effects of "pyric herbivory," "The interaction between free roaming grazers and fire promotes a moving patch mosaic at the landscape scale that favors biodiversity and pasture quality in grasslands. When grazing ceases completely, one essential component of this old evolutionary disturbance pattern gets lost which might have far-reaching consequences for biodiversity and ecosystem processes" (op. cit. p. 2557–2558). Dara et al. (2019) demonstrated through remote sensing that the decrease in grazing pressure in northern Kazakhstan was associated with increased fire prevalence due to accumulation of dry vegetation, with attendant risks of reduced biodiversity. Brinkert et al. conclude quite firmly that "grazing is mandatory to fully restore the original near-natural steppe vegetation and the underlying processes of pyric herbivory" (op. cit. p. 2,544). Hence, we might reasonably assume that "near-natural pastures" are not pristine but instead are evidence that different degrees of biodiversity result from more or less grazing by large wild and domesticated herbivores over thousands of years. "Natural" is therefore difficult to pinpoint.

Larks and Lapwings in the Rangeland

Small bird species, some critically endangered on the IUCN Red List, as well as small mammals and insects, have been closely studied in the contemporary Kazakh rangelands; for example, the Black Lark *Melanocorypha yeltoniensis* (Lameris et al., 2016), White Lark *Alauda leucoptera* and the Sociable Lapwing *Vanellus gregarius* (Kamp et al., 2009, 2015). It transpires that the abundance and community composition of certain species varies depending on whether the sites are heavily-grazed, under-grazed, and in more or less proximity to human settlements (Kamp et al., 2015). The conclusion is that "Heterogeneity in grazing levels, including very heavy local grazing, seems to be crucial for species-rich steppe bird and mammal communities (Kamp et al., 2016, p. 2,530).

Carbon in the Rangelands

Studies from 10 years after the abandonment of state grain farms in the northern Kazakhstan steppe region (Perez-Quezada et al., 2010) found that carbon flux components of net ecosystem exchange were greatest in abandoned crop land, followed by "virgin land" which had not been used for crops (but probably would have been grazed by livestock at some point up to the early 20th C) and least for land sown with fodder crops, wheat or barley. Soil organic carbon was highest for the "virgin lands" and "decreased with greater degrees of cultivation" (ibid. p 91).

Grasslands store more carbon than arable soils because a greater part of the organic matter is physically and chemically stabilized (Soussana et al., 2010). Conversion of croplands back to grazing land results in carbon sequestration which may continue for many decades (McLauchlan et al., 2006). Schierhorn et al. (2019) find that since the end of the Soviet Union there was a large reduction in GHG emissions in the former USSR, including in Kazakhstan, much of which is due to carbon sequestration from abandonment of croplands and reduction of livestock. These soils still have carbon fixation potential because abandoned croplands hold less carbon than native grasslands (Causarano et al., 2011), which sequester additional carbon as vegetation succession proceeds (Perez-Quezada et al., 2010).

Ecologists, wildlife scientists and conservationists familiar with the effects of recent land use changes on the Kazakh rangelands have concluded that one of the main issues for the future is the current "undergrazing" of large areas, which affects how the ecosystem functions and increases fire risk. Restoring free-ranging livestock on the Kazakh steppes, coupled with management advice on ecologically sustainable stocking rates and the heterogeneity of grazing patterns, might result in conservation benefits (Kamp et al., 2016). This view is shared between widely disparate disciplines, in for example, the conclusion reached from archaeological research in Kazakhstan, that "As modern ecologists focus on the restoration or rewilding of grasslands through the re-introduction of wild species to increase biodiversity, a secondary discussion should focus on how animal husbandry might also contribute to grassland ecology" (Ventresca Miller et al., 2020b, p. 11).

DISCUSSION AND CONCLUSIONS

When considering the human impact on rangelands, a key question is what do we mean by "natural"? (Miehe et al., 2014, p. 190). The rangelands of Kazakhstan have been partly shaped by pastoralists' livestock, in addition to being molded by forces of past climate change, wildlife, erosion and deposition, amongst other forces. Therefore, at what point in the past do we demarcate these landscapes as "natural" in the sense of pristine and unchanged by people? A growing body of interdisciplinary literature—combining archaeology with natural and social sciences—refers to these human-environment interactions as "the pastoral niche construction" (Lezama-Núñez et al., 2018) and "ecosystem engineering" (Ventresca Miller et al., 2020b). What does this mean for the future of livestock management and the environment on the rangelands?

The influence of pastoral nomadism on the formation and dynamics of rangeland environments in Eurasia is comparable to that of the East African savannahs as far back as 4,000 years ago (Marshall et al., 2018). Similarly, pastoralism has shaped the high grass plateaus of Asia over millennia (Miehe et al., 2014), and in historic times the pampas of South America (Modernel et al., 2015) and grasslands of Europe (Benthien et al., 2018). To consider the present and near-future impacts of livestock on rangelands, we need to adjust the length of our focus to a long time scale into the pre-historic past—to take "*the longue durée*" (Braudel and Wallerstein, 2009).

Large-scale livestock movement in the Eurasian climate and environment has only been possible with large flock/herd sizes. This scale of collectively-managed animals has been made possible through three "modes of production"—kinship-based, state, and capitalist. Humans have shaped the landscape and ecology of what has, latterly, been defined as a natural environment. The history of the Kazakh pastures reveals how in order to preserve the natural, we have to create the social conditions for collectively managed mobile livestock. These conditions are currently imperiled by administrative and economic constraints facing small-scale rural households.

A

B

FIGURE 8 | (A) New ground water pump and livestock drinking troughs installed by owner with several thousand head of livestock, Moiynkum region, south central Kazakhstan, 2014. Photo: Carol Kerven. **(B)** Soviet era shepherds' wagon and motorbike, with new 4X4 truck belonging to large-scale "fazenda" Kazakh rancher in Moiynkum region, south central Kazakhstan, 2015. Photo: Carol Kerven.

Kinship-based nomadic pastoralism up until the beginning of the 20th century underpinned the mobile exploitation of pastures that were seasonally, annually, and geographically variable across an enormous territory that required military vigilance. In the Tsarist period, use of the extensive scale of heterogenous and wide-open spaces required a social scale larger than that of an individual family, for sharing herding labor requirements and defense against incursions. Consolidation of Tsarist and then Soviet authority over the territory then obviated indigenous political groups' need for defense from other groups. Following a devastating hiatus in the late 1920s and in the 1930s, the national and supranational state (USSR) then assumed administrative, technical, and financial responsibility for re-engineering long-distance seasonal livestock mobility. In these state livestock farms, specialist livestock management activities were assigned to a professionally-trained and centrally managed labor force supported by external capital and scientific research. The demise of central state obligations in the early 1990s initially left individual rural households bereft of necessary resources to resume seasonal livestock mobility. But rising national wealth, new laws and individual initiative has meant that a small proportion of livestock owners are again following some of the old nomadic trails, albeit with mobile telecommunications, hired herders and SUVs, bolstered by public and private financial investment from urban sources **Figure 8**.

In the contemporary period, narratives, and cultural symbols e.g., yurts, are used to reify Kazakhs' ethnic identity in a "cult of mobile pastoralism as national folk culture" (McGuire, 2013), appropriated by popular media, and proffered by some politicians and scholars as a unifying nationalistic theme (Schatz, 2004). However, in current times, "Should a sheepherder abandon the steppe for the city, they would likely find themselves treated not as a cultural hero but as an impoverished and disregarded laborer" (McGuire, 2013, p. 26).

The 21st century brings new opportunities but also challenges for Kazakh rangeland management. At present, only a small minority of livestock owners can and do undertake long-distance seasonal migrations with their private livestock, for reasons outlined in this paper. We have argued here that maintenance of flock and herd mobility requires a level of labor inputs and capital goods, operating within structured social-economic and political institutions. The Soviet collective farm experiment demonstrated that new technology and capital infrastructure could substitute considerably for labor inputs. The picture at present is that individual wealthier livestock owners are replicating this pattern, through investment of private capital increasingly assisted by state and international capital. The impediment to increasing livestock mobility nationally is that the majority of livestock owners have herds and flocks that are too small to justify their individual investment in the technology (mainly heavy transport and developing water points) necessary for longer-distance livestock mobility (see **Figure 7A**). Many smaller livestock owners must continue to graze and fodder their livestock mostly around settlements, with severe environmental impacts.

Increasing the proportion of livestock feed supplied by farmed fodder in relation to grazing on pastures—has been a driving force since the 19th C under the Russian administration, followed under the Soviet state farms which invested capital into forming industrialized nomadism, highly subsidized by central USSR funding from Moscow, and now again with state subsidies targeted to the bigger livestock owners. In each instance, the aim was to stabilize productivity by introducing new sources of feed, while continuing to benefit from lower-cost feed by grazing the rangeland environment. The temptation to intensify is strong—to supress variability and raise livestock output– but eventually there are social and environmental impacts, as reviewed here.

A fine-grained longitudinal analysis (1985–2017) over a large rangeland and farming region of northwestern Kazakhstan showed that "Recent increases in livestock numbers did not translate into major increases in grazed area, suggesting that the intensification of livestock systems, with feedlot-based livestock fed by crops, is playing an increasing role" (Dara et al., 2020, p. 11). Financial inducements—e.g., subsidies for growing feed crops—may shift larger producers' livestock management decisions, by tilting the balance of costs and returns away from mobile seasonal grazing. As an alternative, Kamp et al. (2015) recommend that instead of converting (or re-converting) pastureland to fodder crops, currently unused pastures might be accessed by livestock in the optimal seasons, which would allow "more transient grazing patterns (thereby creating a mosaic of different grazing intensities)" (ibid. p. 1,584).

Given that Kazakhstan still contains a large share of the world's remaining "near-natural" temperate grassland (Kamp et al., 2016), how the Kazakh steppes, adjacent deserts and mountains are managed has global implications for plant and animal biodiversity, carbon stocks, and at a national level for the well-being of Kazakhstan's people and the economy.

The question remains as to whether it will be possible for the majority of livestock owners in Kazakhstan, who also own most of the livestock, to regain the system of mobile livestock management which their ancestors practiced. Only a few are able to do this now. It seems that capitalism can only achieve the necessary scale of herding congruent with the environmental scale by concentrating resources on individuals and corporate groups. But this creates further inequality between herders based on their wealth status, and leads ultimately to environmental degradation, as those individual livestock keepers left behind are condemned to over-exploiting the narrower base of rangeland resources still at their disposal.

AUTHOR CONTRIBUTIONS

CK conceived the paper and prepared the first drafts. RB provided theoretical ideas and research experience among pastoral nomads, including in Kazakhstan. SR contributed new information and research findings from Kazakhstan. All authors have worked together on research in Central Asia over several decades.

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Mobilizing Ecological Processes for Herbivore Production: Farmers and Researchers Learning Together

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Grazing plays a key role in reducing the external inputs required for ruminant production and in alleviating feed-food competition. Beyond the production of meat and milk, grassland-based systems provide a wide range of ecosystem services. Agroecology and organic farming aim to reconcile natural resource management and food production, in the long term, based on the management of ecological processes. In this perspective paper, we report what we have learned from case studies with beef cattle, sheep, and dairy cattle across Uruguay and western Europe, in which we have been involved. Multicriteria methods, such as Pareto frontiers and positive deviances, were used to analyze trade-offs and identify win–wins from farm surveys. Long-term farm networks coupled with bioeconomic optimization models revealed fluctuations in farm income and allowed estimating system resilience. Extensive farmlet experiments made it possible to integrate knowledge on animal physiology and grassland ecology in the system redesign process and to test for innovative and risky management options that could lead to unacceptable learning costs in commercial farms. Finally, learning from farmers' local knowledge in teams with researchers and technical advisers can provide positive changes in grazing systems. In Uruguayan family farms, for example, the scientific knowledge gained from farmlet experiments led to advice on management options based on farm-specific diagnosis. Farmers adapted the proposals, with researchers supporting the processes by providing quantitative information on consequences and spaces for reflection. In a French cheese production area, the focus was on farmers' own experience. Games facilitated interactions as participants could challenge each other's reasoning and conclusions in a safe environment. These two case studies illustrate the diversity of co-innovation approaches, but in both cases knowledge sharing between researchers, farmers, and other stakeholders appeared more efficient to help farmers understand and adapt their own system properties than researching "best practice" solutions for large-scale transfer.

Keywords: agroecology, co-innovation, grazing, management, trade-offs

INTRODUCTION

As a result of the increasing consumption of meat and milk, livestock farming systems face unprecedented pressure to alleviate their negative impacts on the environment. Recent IPCC (Intergovernmental Panel on Climate Change) reports (https://www.ipcc.ch/2019/), and various scientific publications (e.g., Aleksandrowicz et al., 2016; Mottet et al., 2017; Springmann et al., 2018; Dumont et al., 2019; Leroy et al., 2020), have framed the debate in terms of a tension between food security objectives, consumption ethics, and the damaging environmental and climate impacts associated with livestock production. Domestic herbivores, especially cattle, contribute to 14.5% of human-induced greenhouse gas (GHG) emissions (Gerber et al., 2013), and livestock production systems occupy 2.5 billion ha of land, which is approximately half of the global agricultural area (Mottet et al., 2017). The largest share of this area is comprised of grasslands, with almost 2 billion ha. In these grassland-based systems, herbivores transform feed resources that are not directly edible by humans into proteins, vitamins, and long-chain polyunsaturated fatty acids that help to fulfill our nutritional requirements (Mottet et al., 2017; Leroy et al., 2020).

Long-term carbon storage in soils, under permanent grazing lands, has a positive effect on the mitigation of climate change, soil fertility, and soil stability (Lal, 2004; Wiesmeier et al., 2019). In addition, grassland-based systems provide a wide range of ecosystem services (Rodríguez-Ortega et al., 2014), including unique cultural services such as landscape aesthetics, gastronomic heritage, and educational and spiritual experiences (Oteros-Rozas et al., 2014; Huber and Finger, 2020). Grassland-based agroecological (Dumont et al., 2013, 2020; Duru and Therond, 2015) and organic (Bouttes et al., 2019) farming systems are thus expected not only to reduce the external inputs required for meat and milk production, including soybeans and corn for animal feeds, mineral fertilizers, and energy, but also to provide a more balanced portfolio of ecosystem services than intensive production areas (Foley et al., 2005; Dumont et al., 2019). This, however, requires adequate management of herds and grasslands.

Managing the key ecological processes, to be optimized in grassland-based systems, is likely to lead in the direction of a strong form of ecological modernization, but it is also knowledge intensive. However, despite the vast amount of knowledge already accumulated on complex and changing systems, there is still limited emphasis on understanding how to learn and implement desirable transitions benefiting from these ecological processes (Geertsema et al., 2016; Rossing et al., in review). It implies learning about and monitoring of interactions among system components, developing new skills and field tools (Duru, 2013), and participatory methods to benefit from farmer experience (Berthet et al., 2016). Indeed, agroecology places strong value on local knowledge and places farmers as the designers of their production system (Rosset et al., 2011; Dumont et al., 2013, 2018; Prost et al., 2018). Engaging with farmers and other local stakeholders to generate "actionable knowledge," that is, "knowledge that specifically supports stakeholder decision making and consequent actions" (Geertsema et al., 2016), allows for the fostering of agroecological innovations. This implies integrating farmers' practices, perceptions, and values (Kosgey et al., 2006; Coquil et al., 2018), accounting for the singularities of the local production system to be transformed, e.g., edaphic and climatic conditions, new demands for products and markets (Oosting et al., 2014), and disseminating knowledge among local communities and regional stakeholders (Albicette et al., 2017). The "how to" question thus involves changes in the perspectives and values that underlie perceptions of how things need to be done (Tittonell et al., 2016).

In this perspective article, we report what we have learned from some case studies with beef cattle, sheep, and dairy cattle across western Europe and Uruguay, in which we have been involved (**Figure 1**). According to Eurostat 2010, grassland-based production areas accounted for 34% of the European herd (mainly ruminants) on 31% of the EU-wide utilized agricultural area (Dumont et al., 2019). Our case studies are located along a gradient from the most intensive areas with dairy cows (in the Netherlands) or sheep (Ireland), to intermediate- and low-density areas in French Massif Central uplands and Mediterranean grazing lands where ruminant systems deliver many regulating and cultural services. Campos grasslands occupy 700,000 km² in South America. The cow–calf system is the main livestock activity in this region, mainly in family farms (Modernel et al., 2016). Farmers raise animals for meat, and finishing takes place on-farm at pasture.

These case studies of grazing system transition to agroecological or organic systems reveal three complementary research approaches. First, the use of farm networks and farm system models generates generic knowledge by investigating the complexity, diversity, and long-term dynamics of grassland-based agroecosystems. Second, farmlet experiments allow production of technical and practical knowledge under long-term and well-controlled settings. Third, participative situations where farmers team up with researchers and technical advisers in identifying the main system problems and implementing options to improve them are likely to generate situational knowledge with a territorial scope. These different case studies reveal different modes of actionable knowledge production according to different modes of involvement of researchers with farmers.

LEARNING ABOUT SYSTEM COMPLEXITY AND TRADE-OFFS USING FARM NETWORK DATA

The use of farm network data facilitates learning about the complexity of agroecosystems from long-term series and/or from farms covering a gradient of pedoclimatic or management conditions. Farm system models allow the exploration of farm resilience. An original approach for capturing innovations occurring in commercial farms comes from the "positive deviants" approach (Sternin and Choo, 2000), where farmers identify peers with outstanding economic and environmental performance.

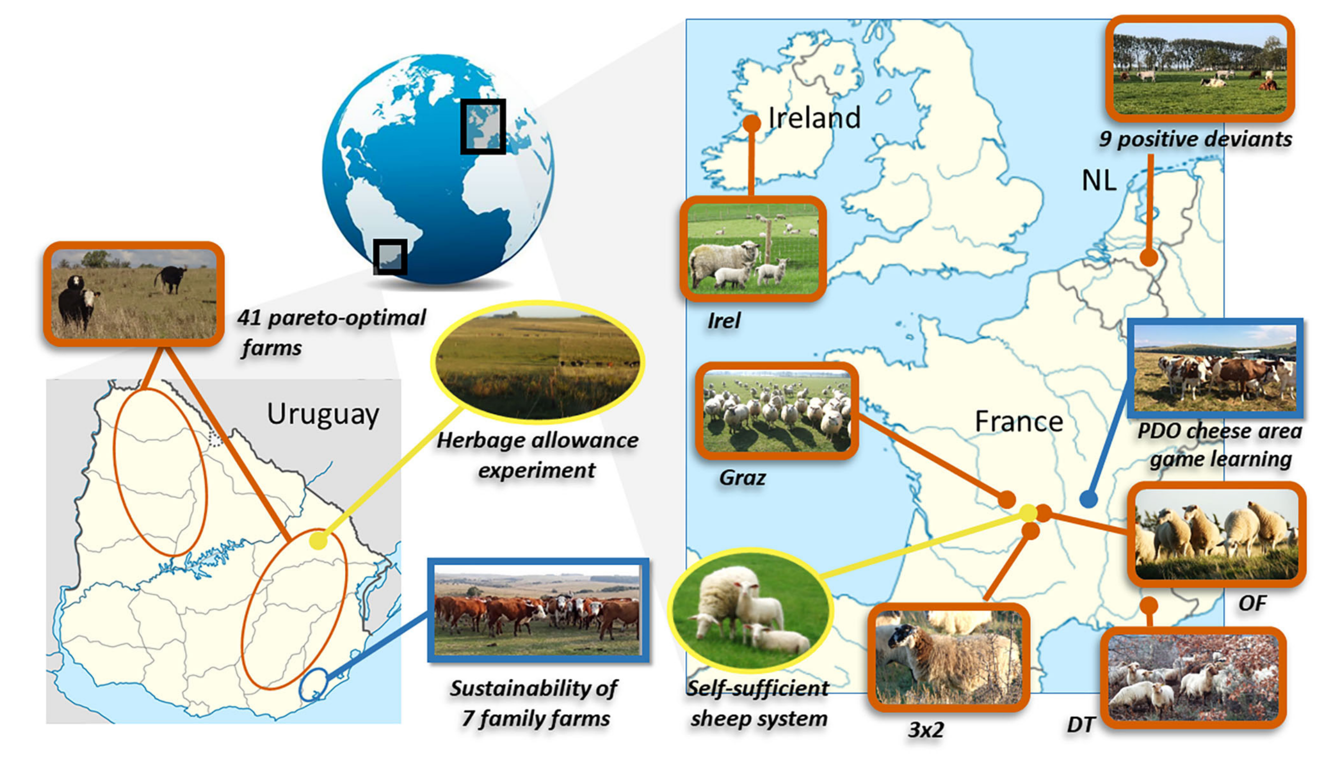

FIGURE 1 | Location of case studies. Brown rectangles are farms where trade-offs were analyzed, yellow ovals are long-term system experiments, and blue rectangles indicate a co-innovation approach.

Pareto Frontiers Identify Farms That Outperform Others in Several Dimensions

Multicriteria optimization methods such as Pareto frontiers have been successfully applied in various types of agricultural landscapes (Groot et al., 2012; Andreotti et al., 2018; Verhagen et al., 2018) to identify management options or farms that outperform others. In the Rio de la Plata grasslands, Modernel et al. (2018) identified outstanding beef farms in terms of economic and environmental performance. Performance was assessed through indicators built from field data and interviews collected from 280 farms. These farms were representative of the diversity of the farming systems of the region when contrasted with a typology based on census and large-scale farm surveys. Two methods were applied to classify the farms in both economic and environmental terms. First, through Pareto ranking, 41 farms were classified as Pareto optimal, i.e., outperforming the other farms. In a second step, four archetypes were created based on Fischer et al. (2017) production-biodiversity framework (Fischer's, 2017) and experts' threshold values. Five farms were classified as "win–win" farms, achieving beef yields of 192 kg LW.ha^{-1}.year^{-1}, earning 201 US\$.ha^{-1}.year^{-1} of farm income, with negligible fossil energy consumption, near-zero phosphorus and nitrogen balances, 13 kg CO_2-eq kg^{-1} LW of carbon footprint, and 95% of their land under native, high-biodiversity grassland. These five farms were all Pareto-optimal, which showed the complementarity of both methods in identifying multidimensionally best-performing farms. Putting this analysis in perspective, the win–win farms showed similar levels of production per hectare and carbon footprint (per kg LW) to those of the OECD countries but with significantly lower levels of fossil fuel consumption. This is explained by the low use of external feeds and inputs, making these farms of Río de la Plata grasslands an example of self-sufficiency.

Analyzing Multiperformance and Resilience in a Long-Term Farm Network

Though not formally using Pareto frontiers, Benoit et al. (2019) selected three sheep-meat farms with outstanding performance out of 118 commercial farms from central France encompassing both lowlands and uplands. These farms were surveyed for an average of 12 years and characterized based on two key variables that are good proxies for farm efficiency: concentrate feeds used per ewe and per year as these represent the main production cost for sheep farming (64% of costs in this farm network), and ewe annual productivity that is highly correlated with farm net income (Benoit and Laignel, 2011). The selected farms were *Graz,* a grazing system in the French western lowlands; *3x2,* an accelerated reproduction system with three lambings every 2 years in the upland area of Massif Central; and *OF,* an organic farm from the same area but with more shallow soils. Two other farms, *DT*, a dual transhumant system in French Mediterranean rangelands (Vigan et al., 2017), and *Irel,* a Teagasc experimental farm in Ireland (Earle et al., 2017), were selected to

TABLE 1 | Main characteristics of the five farms, including their structure, flock management strategy, and economic and environmental performance [adapted from Benoit et al. (2019)].

	Irel	Graz	3x2	OF	DT
Total area (ha)	36.8	81.9	53.9	91.9	4463
Stocking rate (ewe/ha)	11.4	6.6	8.7	4.4	0.5
FLOCK MANAGEMENT					
Ewe annual productivity %	154	133	166	132	82
Concentrates (kg/ewe)	36.5	42.2	134.6	77.1	0.0
Concentrates/kg carcass	1.22	1.55	5.24	3.41	0.00
Feed self-sufficiency (%)	94.9	94.3	78.2	88.1	100
ECONOMIC PERFORMANCE					
Gross margin (€/ewe)	89	132	121	115	74
Production costs (€/LU)	555	533	642	794	483
Added value (€/worker)	21,400	31,700	19,800	22,500	31,900
ENVIRONMENTAL PERFORMANCE					
Gross GHG (CO_2-eq/kg carcass)	21.7	18.3	22.5	24.8	28.6
Net GHG (CO_2-eq/kg carcass)	19.2	13.7	16.6	8.5	−130
NR Energy (MJ/kg carc.)	50.6	31.4	50.9	47.6	22.7
HEP conv. efficiency (%)	158	125	33	51	∞

Irel is for the Irish system, Graz is for grazing, 3x2 is for accelerated reproduction system, OF is for organic farming, and DT is for dual transhumant system. NR Energy is for non renewable energy. HEP conv. efficiency is for human edible protein conversion efficiency (Ertl et al., 2015).

extend biogeographical conditions and the stocking density range (**Table 1**).

The two farms relying the most on grasslands and rangelands (*Graz* and *DT*) showed the best economic and environmental performance (Benoit et al., 2019). Farm profitability was assessed from added value per total worker as it does not account for subsidies or wages and social costs and thus reveals the ability of the system to produce sheep meat with the maximum utilization of on-farm resources. These two farm added values were the highest thanks to a strong reduction (*Graz*) or complete avoidance (*DT*) of concentrate feeds, reducing production costs (**Table 1**). In addition, limited equipment (due to the absence of fodder stocks) and buildings led to the lowest production costs for *DT*. *Graz* and *DT* had the same added value but with contrasted production objectives, ewe productivity being 38% lower and gross margin per ewe 44% lower in *DT* than in *Graz*. Gross GHG emissions per kg carcass were the lowest in *Graz* at 18.3 kg CO_2-eq kg^{-1} carcass thanks to its high ewe productivity and limitation of inputs. When accounting for carbon sequestration in grasslands and rangelands, net GHG was among the lowest for *OF* (8.5 kg CO_2-eq kg^{-1} carcass) and even became negative for *DT*, which had a positive carbon balance. The Irish system also followed a forage autonomy strategy but with poorer environmental and economic performance due to mineral fertilization, higher prices of land, and lower meat prices (Benoit et al., 2019). Concentrate feed consumption was the highest in the highly stocked and accelerated reproduction *3x2* system, where 10.1% of the total proteins consumed by ewes were human edible, which demonstrated significant feed-food competition. Conversely, calculating the human edible protein conversion efficiency (Ertl et al., 2015) showed that the three farms that followed a forage autonomy strategy (*DT, Irel*, and *Graz*) yielded more human-edible proteins in meat than they utilized for producing it (**Table 1**). The high seasonality of lambing associated with these systems revealed a new type of trade-off between farm multiperformance and the meat industry demand for a regular meat supply throughout the year (Benoit et al., 2019) and would require adjustments in consumer demand (Singh-Knights et al., 2005).

By using a bioeconomic optimization model, Benoit et al. (2020) explored the resilience of these five farms. Simulated hazards were related to technical (ewe fertility and prolificacy, lamb mortality) and economic variables (price of lambs, concentrate and energy use). Farm performance was assessed over 3000 iterations based on simultaneous random draws with hazards related to these variables. Farm resilience was estimated from the (i) coefficient of variation of net income and (ii) frequency of two or three successive years with a drop in income. Variations in technical variables had the largest effects on income variability. The most resilience farms were those where ewes were fed little concentrates, and two or more lambing periods were planned every year, i.e., *DT*, *OF*, and *Graz*. Multiperiod lambing indeed buffered the variability of technical variables and offered adaptive management options to cope with them, i.e., moving empty ewes to a new batch for re-mating in order to maximize ewe annual fertility.

Identifying Farmer Excellence Criteria From a Positive Deviance Approach

In a case study on organic dairy farming in the Netherlands (de Adelhart Toorop and Gosselink, 2013; Rossing et al., 2019), the concept of "positive deviants" (Sternin and Choo, 2000) was used to identify farmers who, according to their peers, were exemplary. A selection of these farmers was then approached, and their farms were characterized in terms of economic and environmental performance. The aim of the study was 2-fold, firstly to identify criteria that farmers considered relevant for evaluating farm performance, and secondly to assess to what extent peer-nominated exemplary farms stood out when using science-based analytical approaches. Through a web-based questionnaire, farmers were asked to rate the importance of 12 predefined and any self-proposed additional criteria when considering good farm management. The predefined criteria were derived from the literature, experts and experience. In the next step, respondents were asked to identify the top 5 criteria and nominate farmers that they considered exemplary according to these criteria. The results showed good soil management, low use of antibiotics, income, pasture time, and climate-friendly factors to represent the top 5 indicators for positive deviance according to the dairy farmers. Respondents nominated 34 peer farmers as exemplary, some multiple times. Out of the list of these nominated farmers, three experts selected nine farms that were approached for a semi-structured interview in which more details were collected on the farmer criteria and for multi-criteria evaluation using the FarmDESIGN bioeconomic model

(Groot et al., 2012). Analysis of the nine selected farms revealed consistently long grazing seasons, low use of maize silage, positive soil organic matter balances, relatively low replacement rates of 22%, and medium-level milk production in comparison to organic or conventional averages (Rossing et al., 2019). An interesting conclusion is that farms identified by peer farmers as exemplary farms managed to balance the various performance indicators rather than excel in specific ones, except for the low or no use of antibiotics (Rossing et al., 2019). The peer-nominated exemplary farmers achieved their status by drawing on internal farm resources related to grazing and soil organic matter supply, with limited use of maize silage. The "art" of doing so with less inputs was thus reflected in peer appreciation and revealed a convergence between farmer and researcher excellence criteria.

LEARNING BY DOING IN WELL-CONTROLLED SETTINGS

Long-term farmlet experiments allow "learning by doing" in well-controlled settings. A first case study in French Massif central uplands consisted of four successive cycles of farmlet experiments that were conducted between 1988 and 2009 to design a self-sufficient and sustainable system for upland sheep production. Analytical trials were associated with the main experiment for exploring some of the biotechnical limiting issues, such as how to implement the ram effect to maximize ewe fertility for spring mating (Tournadre et al., 2002). Outputs from the system experiment were compared with technical and economic references from a network of commercial farms in the same study area (Benoit and Laignel, 2011). A second case study from the Campos grasslands illustrates how knowledge of animal physiology and plant–herbivore interactions was used to propose a conceptual model of herd and grassland management (Soca and Orcasberro, 1992) that was then tested on two experimental farms.

Farm Extensification and Transition to Organic Farming in Upland Sheep Systems

At the end of the eighties, European regulation policies were introduced into the livestock sector, including subsidies to support farming in marginal areas. These areas of low agronomic potential were gradually abandoned, which led the European Commission to set up an incentive measure to decrease stocking density by enlarging the farm area. A new research program was set up at Redon experimental farm (https://doi.org/10.15454/1.5572318050509348E12) to design a sustainable sheep system in this context of farm "extensification." We opted for a systemic approach to ensure system consistency. The first phase (1988–1992) of the experiment (**Figure 2**) aimed to adjust available forage resources to animal requirements when the available area per ewe was increased by 40%. Two farmlets (F1 and F2) were compared with the same flock size (130 Limousin ewes), one lambing per ewe and per year (2/3 in spring, 1/3 in autumn to match resource availability and optimize ewe annual productivity), and two stocking rates: 1.20 LU ha^{-1} for F1 and 0.85 LU ha^{-1} for F2. The same treatments were applied for 5 years to allow medium-term ecological processes such as shifts in plant community structure and animal adaptations. Extensification did not reduce ewe productivity and increased lamb carcass weight by 6%, despite a 26% decrease in concentrate feeds per ewe and per year. Gross margin per ewe was on average 27% higher in F2 than in F1. Three-quarters of the gross margin gain in F2 could be directly related to this 50% reduction in input costs (including mineral fertilization) that compensated for the structural costs of renting additional land. However, technical, and economic results were variable and required anticipation of management decisions and a greater technicity, especially for fodder resources (Thériez et al., 1997). Despite European incentives, only a few farmers opted for this extensification strategy. One farm from the reference network (Benoit and Laignel, 2011) did so in 1994 by increasing farm area by 20%. This farmer's net income increased by 10% per hectare between 1988–1989 and 1994–2002 thanks to a better control of production costs, which was higher than the 5% average increase reported for the 28 other sheep farms from the same area.

A second phase of the research (1993–1998) aimed at assessing the feasibility of further reducing the stocking rate. Two new systems were created with grazing at a very low stocking rate of 0.6 LU ha^{-1}. In F3, management aimed at optimizing the use of grasslands and meat production by keeping the same reproduction rhythm as in F2. As the pasture utilization rate (i.e., the ratio of grazing pressure to maximum standing biomass) was only 37% at 0.6 LU ha^{-1}, an additional goal of limiting scrub encroachment was added in F4. Grassland management led to (i) reducing farm-scale N inputs by 70% with no mineral fertilization in plots where grassland management was assumed to favor white clover; (ii) grazing early, ewes returning to pastures every 3 weeks during spring so that they browse young shoots of broom; (iii) controlling grass growth by early cuts for stocks in spring; (iv) grazing far-away plots in late spring and summer to limit shrub encroachment; and (v) grazing during winter to exploit residual herbage and preserve sward quality (Brelurut et al., 1998; Louault et al., 1998). Shrub encroachment was twice as slow in F4 as compared with F3, while system technical and economic performances were excellent for upland areas, with a 153% increase in ewe annual productivity (Dedieu et al., 2002) and only 59 kg of concentrate per ewe and per year (Brelurut et al., 1998). Lambs and lactating ewes that are more susceptible to strongyle infection were excluded from pastures grazed during the previous winter. Stock management secured the system and produced high-quality hay for lactating ewes and spring lambs that were fattened at pasture.

At the end of the nineties, organic farming was seen as an opportunity to (i) respond to an emerging societal demand and (ii) simulate innovations that would make sense in a context of exploding input costs. A third phase of the research (2000–2004) thus aimed at comparing two organic systems with a stocking rate of 0.8 LU ha^{-1} but differing in ewe reproduction rhythm. The first system was based on one lambing per ewe per year (F5), lambing being equally distributed in two periods, March and November. The second system tested an accelerated reproduction strategy with three lambings every 2 years (F6) to

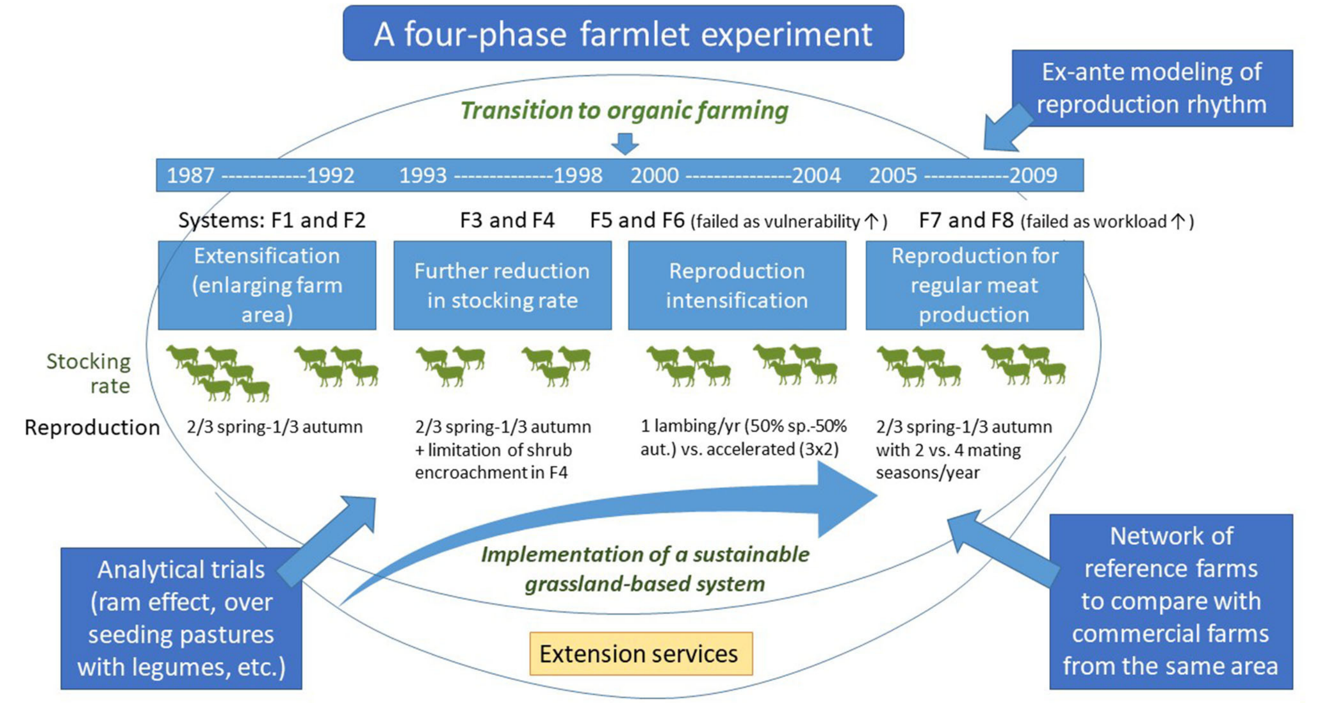

FIGURE 2 | The four successive cycles of farmlet experiments that were conducted in French Massif Central to design a self-sufficient and sustainable system for upland sheep production.

maximize ewe productivity, as observed in conventional farms from this area (i.e., *3x2* in Benoit et al., 2019; **Table 1**). In F6, ewe annual productivity was higher (161 vs. 151%) but also more variable than in F5. Ewes faced more health issues (digestive strongyles and coccidia) in F6, and lamb mortality was higher (Benoit et al., 2009). Lamb carcass weight was on average 3% less in F6 than in F5. The total concentrate per ewe was 29% higher, so the gross margin per ewe was lower in F6 than in F5 at 59 vs. 65 €, respectively. Benoit et al. (2009) concluded that reproduction intensification in an organic sheep farm did not improve economic performance and even increased system vulnerability. The less intensive reproduction system F5 had a high technical efficiency and was highly self-sufficient. The technical and economic performance of this system was better than that of commercial organic farms from the same area and similar to that of conventional farms.

The fourth phase (2005–2009) aimed to refine the reproduction rhythm to ensure regular meat production in this self-sufficient organic system. A bioeconomic optimization model (Benoit et al., 2014) suggested dividing flock mating over four (F8) rather than two periods per year (F7: 2/3 in spring, 1/3 in autumn for both systems). Putting this idea in practice led to a good utilization of forages but failed due to increased workload and difficulties in optimizing grass use with very small batches of sheep grazing large plots. Overall, this long-term farmlet experiment made it possible to incrementally develop a sustainable system for upland sheep production. Some risky options were successful, while others proved to increase system vulnerability or workload and were therefore rejected. The organic system with one lambing per ewe per year was implemented on the same land at 0.8 LU ha^{-1} by a commercial farmer at the end of this experimentation (*OF* in Benoit et al., 2019) and maximizes grass utilization with 60% lambing in spring and 40% in autumn.

Managing Herbage Allowance and Cow Body Condition in Campos Grasslands

In Uruguay, family beef cattle farmers in Campos grasslands suffer from unsustainable economic performance and degradation of these natural grasslands. The sustainability of the cow–calf system is related to the management of the cow body condition score (BCS), which influences the weaning rate. Reduced energy intake causes lower BCS at calving and lengthens postpartum anoestrus (PPA); it also decreases pregnancy rate, meat production per hectare, and farm profitability (Soca et al., 2007). Herbage production variability within and among years, together with the relatively high stocking rate traditionally used in the cow–calf system, explains why cows usually do not achieve optimum BCS at calving. Herbage allowance (HA) in kg of herbage DM per kg of animal liveweight (LW; Sollenberger et al., 2005) appears to be a relevant variable for system management. Decreasing the stocking rate leads to a higher herbage allowance from calving in spring to calf weaning in autumn (Soca and Orcasberro, 1992; **Figure 3**), which is likely to rapidly increase BCS after calving and thus shorten cow PPA and improve the pregnancy rate. This is also assumed to benefit calf weight at

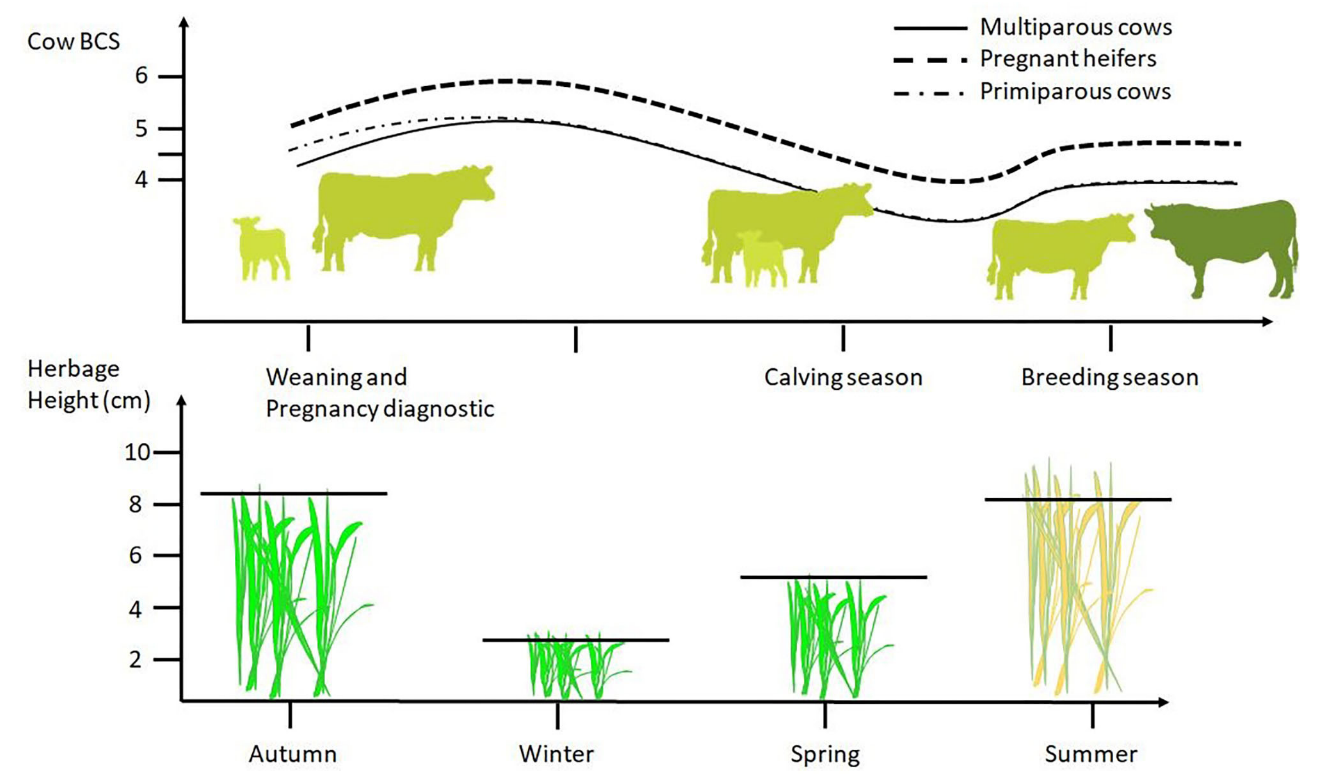

FIGURE 3 | Proposed model for the management of cow body condition (BCS) and herbage height in Campos grasslands (adapted from Soca and Orcasberro, 1992). Horizontal bars in the lower part of the figure indicate target sward heights.

weaning, meat production per ha, farm economic outputs, and ecosystem services due to a better soil cover and higher sward structural heterogeneity (Do Carmo et al., 2016).

The first phase in this research consisted of designing a grazing experiment with factorial treatments to evaluate the effects of (i) changing herbage allowance during the grazing season and (ii) using suckling restriction by fitting nose plate devices 11 days before the start of the mating period on the cow pregnancy rate and calf weight at weaning. It was confirmed that suckling restriction could shorten PPA and improve the pregnancy rate for cows with low BCS at calving (Soca et al., 2007). The second phase of this research aimed to understand the underlying metabolic mechanisms and to define when and how suckling restriction should occur. Knowledge in animal physiology suggests that (i) suckling restriction is assumed to reduce PPA by reducing cow milk production and energy requirements and by increasing circulating insulin and (ii) suckling restriction should be applied after cow energy balance nadir (55 days postpartum) when nutrient partitioning changes toward anabolic processes (Soca et al., 2007). This led researchers to investigate the consequences of suckling restriction for 12 days, from 60 to 72 days postpartum, associated with short-term (22 days) energy supplementation ("flushing" with 2 kg DM of rice middling per cow and per day) after the energy balance nadir, as a management strategy to redirect energy toward reproductive functions. Such interaction between suckling restriction and flushing appeared to be a cheap (4–10 US$ cow^{-1}) way of improving pregnancy in "thin" primiparous cows. Suckling restriction reduced milk production, which was associated with an immediate 2-fold increase in plasma IGF-I (insulin-like growth factor-I) concentrations (Soca et al., 2013b). Cow BCS at calving modulated plasma insulin and IGF-I concentrations. The metabolic response to flushing differed between cows in moderate vs. low BCS, cows with BCS lower than 4 showing poorer pregnancy rates than those in slightly better conditions (Soca et al., 2013a). Outputs from this research defined the optimal BCS targets that make manipulations of herbage allowance successful for improving cow reproductive performance (**Figure 3**).

Once these metabolic adaptations were understood, the third phase of the research consisted of testing for the effects of two levels of HA (high: HHA vs. low: LHA, which annually averaged 4 vs. 2.5 kg DM kg^{-1} LW) on cow productivity in two farms to widen environmental conditions. In one farm, multiparous cows aged 4–8 years were used, and F1 reciprocal Hereford and Angus crosses were compared with Hereford and Angus cows (Do Carmo et al., 2018). Purebred primiparous Hereford and Angus cows were used on the other farm with shallower soils (Claramunt et al., 2017). In line with the grazing management strategy summarized in **Figure 3**, herbage allowance varied seasonally. High HA increased calf weight at weaning, pregnancy success, and beef production per ha on both farms. Crossbred Angus and Hereford cattle increased kg of calf weaned per cow and cow BCS (Do Carmo et al., 2018), which confirms previous results (Morris et al., 1987). The farm stocking rate was unaffected by pasture management on this farm (Do Carmo et al., 2018) but had to be reduced by 25% in HHA compared with LHA when primiparous cows grazed on shallow soils (Claramunt et al., 2017). In this second farm, precipitation during spring–summer had a huge effect on herbage yield. The stocking rate in HHA was lower, but the cow pregnancy rate (88 vs. 59%), calf weaning weight (194 vs. 175 kg; Claramunt et al., 2017), production per unit area, and production efficiency (g calf/MJ energy consumed per cow and per year) were higher in HHA than in LHA (Do Carmo et al., 2016). High HA led to moderate improvements in cow BCS (0.5 units) and energy intake (11%) during autumn. BCS and IGF-I concentrations were greater during winter, which led to more cows ovulating early in the next breeding season and successfully increased the herd reproductive response (Claramunt et al., 2020). This set of experiments has shown how the energy flow can be efficiently used in producing beef by maximizing energy consumption by cows and improving the energy partitioning in the animals (Do Carmo et al., 2016).

LEARNING FROM FARMERS' KNOWLEDGE IN A CO-INNOVATION PROCESS

Reconfiguring farming systems to reduce reliance on external resources and enhance the availability and utilization of farm-internal resources requires rethinking both technological and organizational aspects of the farm. How to make scientific and farmer knowledge actionable for such changes is a key question (Geertsema et al., 2016; Rossing et al., in review). Knowledge sharing logic (Compagnone et al., 2018) aims to reach out to people who are traditionally excluded from scientific knowledge. Taylor and de Loë (2012) showed that scientists' "epistemological anxiety" about local knowledge was a significant barrier to its effective use in decision-making. Moreover, farmers who own local knowledge do not always feel concerned, legitimized, or even competent to contribute to their sector governance (Sterling et al., 2017). Meanwhile, the ecologization of herbivore production requires the consideration of the local context and stakeholder values, such as their relationship to nature (Coquil et al., 2018; Dumont et al., 2018). These particularities call into question the relevance of forms of intervention based on generic knowledge that do not aim for hybridization with local knowledge sources (Landini et al., 2017). We assume that such hybridization of knowledge in new learning modes between stakeholders (Caron et al., 2014; Hazard et al., 2018) would make it possible for them to share experiences and express feedback on practices and observations (Oliver et al., 2012).

Improving Sustainability of Uruguayan Family Farms Through Co-innovation

As previously discussed, research on experimental farms showed that a range of options for grassland and herd management exist that contribute to improving the sustainability of the cow–calf system. Though these advances are potentially powerful levers (Do Carmo et al., 2016; Modernel et al., 2018), uptake of the findings has been slow if not absent. It was hypothesized that a key element for the low adoption was that the scientific findings were not presented in an integrative, farm system perspective and were difficult to make locally salient for the farmers (Albicette et al., 2017). This analysis prompted a project in which a multidisciplinary team of researchers, advisors, and cow–calf family farmers worked closely together over a period of 3 years (Ruggia et al., in review). The participatory action research methodology (Moschitz et al., 2015) was used as a novel way of addressing complex agricultural problems while contributing to building capacities inside the team. Farm visits, at least monthly, supported the data gathering and mutual trust building needed to characterize, diagnose, and ultimately redesign the farms of seven participating farmer families. Beyond the farm level, half-yearly meetings were organized with selected actors from regional and national governance organizations, referred to as the inter-institutional network. The meetings served to inform these actors of the on-farm developments, thus connecting to much wider networks to enhance the spread of the results and to build the necessary institutional changes that would support farmers beyond the project's lifetime. The seven farmers had finished primary school and were on average 50-year-old (range: 37–59). At the level of the 17-person research team, meetings were held monthly to evaluate past activities in terms of both quantitative changes and changes in the attitude and skills of participants. The project thus combined a system approach with monitoring for learning while creating a setting that supported learning about new technologies and social arrangements, together denoted as a co-innovation approach.

Proposals for redesign of the seven farms were based on changes in management practices without adding external inputs and without increasing costs. The main strategy elaborated with and implemented by farmers was to increase standing biomass and forage production of the grasslands by managing the grassland–herd interaction, increasing herbage allowance (HA) and adjusting allocation of animal categories to different paddocks according to standing biomass. Associated with suckling restriction and flushing, HA management modified energy partitioning between production and reproduction, which increased the efficiency of cow energy use (Soca et al., 2013a,b; Do Carmo et al., 2016; Claramunt et al., 2017, 2020). Management of HA required variation of stocking rate and/or sheep-to-cattle ratio at the paddock or system scale and monitoring of standing biomass. Farmers contributed a lot to the redesign process by providing knowledge about land, soils, animals, and production objectives. At the beginning of the project, they used 39% of the proposed technologies. One year after starting the project, they shifted from "not planning" to starting "mid-term planning". After 2 years of implementation of the redesign proposals, farmers used 97% of the technologies (Ruggia et al., in review). Most farmers were prone to include these technologies, the more difficult ones being adjustments in stocking rate and sheep to cattle ratio (Ruggia et al., in review). On average, farmers decreased the total stocking rate by 8% and the sheep-to-cattle ratio by 42% (**Table 2**). Improvement of the grassland–herd interaction resulted in an increase in standing biomass.

TABLE 2 | Average of the main productive variables of the seven pilot farms at the start (summer 2013) and end (2015) of the co-innovation process [adapted from Ruggia et al. (in review)].

	Start	End	Diff
Total stocking rate (LU/ha)	0.92 ± 0.02	0.85 ± 0.02	−8%
Sheep to cattle ratio	2.6 ± 0.3	1.5 ± 0.5	−42%
Herbage yield (kg DM/ha)	1274 ± 390	2334 ± 344	+ 83%
Herbage allowance (kg DM/kg LW)	3.3 ± 0.2	5.6 ± 1.7	+ 70%
Pregnancy (%)	75.8 ± 3.2	91.5 ± 4.9	+ 21%
Equivalent meat, i.e., meat + wool (kg)	99.5 ± 5.9	121.5 ± 2.6	+ 22%
kg of weaning calf per breeding cow	106.4 ± 13.7	139.9 ± 11.9	+ 31%

Herbage height at the beginning of the project (summer 2012–2013 average) was half the amount required for lactating cows that should get pregnant again (i.e., 6 vs. 12 cm, respectively; Soca and Orcasberro, 1992). Over the next two summers, the average forage height and herbage allowance increased to the recommended values, which increased the herd reproductive response, production per unit area, and production efficiency (**Table 2**). Comparing the average of the 3 years before the beginning of the implementation of the redesign plans with the average of the three subsequent years, the net income nearly doubled from 31.3 ± 18.9 US$ ha^{-1} to 59.5 ± 15.8 US$ ha^{-1}, while production costs were slightly reduced by an average of 3% (from 109.0 ± 14.8 US$ ha^{-1} to 105.3 ± 4.2 US$ ha^{-1}). High standing biomass is also likely to reduce erosion risk and climate vulnerability while increasing soil carbon content. The Ecosystem Integrity Index (Blumetto et al., 2019) evaluates the state of a specific ecosystem under agricultural use in comparison to an optimal state that is established for the ecoregion. It remained stable at 3.7, which represents an acceptable to good environmental status. Finally, labor input decreased by 24% over the course of the project, which, together with the increase in productivity, resulted in an increase in labor productivity (quantity of meat produced per worker) of 97%.

The main lessons learned from the co-innovation experiences in Uruguay are as follows: (i) it is possible to significantly improve the sustainability of family farms within the limitations imposed by their current resource endowment and socioeconomic context by agroecological processes; (ii) to be successful, any change strategy should be adapted to the particular situation of each farm. Such adaptation can be achieved by a systemic process of characterization, diagnosis, redesign, implementation, and evaluation planned as a learning process with the farmers and technical advisers as main participants; (iii) researchers contribute to this process by providing scientific tools and methods to foster the learning cycle (Giller et al., 2008; Groot and Rossing, 2011); and (iv) transition to agroecological systems is a long-term process and requires developing trust between farmers, extension agents, and researchers that only a longstanding relationship can provide.

Using Games in a Local Knowledge Sharing Perspective

In France, knowledge sharing was experienced in a small Protected Designation of Origin (PDO) cheese production area (la Fourme de Montbrison) of Massif Central to build a common vision among multiple local stakeholders. The whole process consisted of six successive steps (Dernat et al., in review). First, the methodology was clearly stated with stakeholders of the PDO area, nearly 60% of all farmers, and the four processors participating in two meetings in February and March 2018. The second step consisted of 2-h interviews aiming at understanding the current concerns and perspectives of 30 PDO farmers and processors. Simultaneously, more than 300 consumers were surveyed online or on local markets for their consumption, cooking habits, and expectations on Fourme quality. The third step consisted of a collaborative day of exchanges in October 2018 with 89 stakeholders (40 farmers: 45-year-old on average [range: 22–68], 25% among the youngest with a technician certificate from agricultural college, all four processors, local officials, vets, agriculture advisors, etc.) on the PDO sector diagnosis and proposals for future actions. Two games were used as collaborative tools. The first one aimed to build a common and spatialized vision of the PDO area (Angeon and Lardon, 2008) and led to the proposal of 53 actions related to animal feeding, use of summer pastures, on-farm processing, cheese sanitary quality (e.g., safety of raw milk), conservation and valorization (e.g., opening a cheese bar), cultural heritage, and governance by a professional organization, the Fourme Union. The second one (called "the barn" because of its pentagonal appearance; **Figure 4**) provided an operational but non-spatialized representation of the PDO production area as a socio-ecological system (Ryschawy et al., 2019). It focused on how local dairy farms interact with their physical, economic, and social environment and allows the identification of synergies and trade-offs between these dimensions. Two scenarios were built, a 2030 business as usual demand and a 2030 demand with better Fourme added value. The two games were thus complementary in the knowledge they provided and allowed the expression of contrasted and sometimes antagonist viewpoints among stakeholders (Dernat et al., in review). Participants shared their empirical knowledge and collectively exercised their analytical skills by learning to position their own vision relative to that of others. In doing so, they learned to propose criteria for evaluating relevant variables and to negotiate with other participants for building a shared vision of the area. Actions proposed during the collaborative day were then submitted to an online vote of the PDO farmers and processors (step 4). The aim was to prioritize actions that were then discussed at two meetings of the Board of Directors of the Fourme Union (step 5), with researchers acting as facilitators. A 10-year strategy was then proposed based on the outputs of the whole process and presented at a meeting devoted to the farmers and processors of the PDO Union (step 6). This meeting allowed individual points of view to be expressed while strengthening the common vision. The strategy was then approved during a general assembly of the Fourme Union in March 2019.

Four major guidelines in the 10-year strategy were as follows: (i) communication focusing on the diversity of the product, reflecting the diversity of production methods and meeting consumer expectations; (ii) improvement of product sanitary quality, in particular the safety of raw milk and the conservation of cheese for a better distribution. This guideline met the expectation of both processors and farmers seeking

FIGURE 4 | Stakeholders from a French PDO cheese production area (Fourme de Montbrison) playing a game adapted from Ryschawy et al. (2019) socio-ecological framework. It allowed the expression of contrasted and sometimes antagonist viewpoints among stakeholders (Dernat et al., in review). Picture by François Johany.

empowerment and wishing to set up on-farm production; (iii) rethinking internal organization of the PDO and its functioning; and (iv) orientation of dairy production toward an agro-ecological and cultural heritage approach. This last point was also the most discussed, as it would imply a transformative approach of the current production system. It is based on an incentive (but not mandatory) to switch to a full-hay diet in at least 60% of PDO farms within 10 years. Production would thus rely on species-rich permanent pastures, which would put the ecological and cultural value of local grasslands, and the link between cattle diet and the sensory and nutritional quality of dairy products, at the heart of the production strategy. The whole collaborative process thus led to the identification and formalization of a common prospective vision for this PDO area within 1 year while accounting for contrasted priorities and values of local stakeholders.

DISCUSSION

Case studies across western Europe and Uruguay allowed us to identify win–win management options for grazing systems in terms of economic and environmental performance. Multicriteria methods, such as Pareto frontiers and positive deviances, were used to identify such win–wins from farm surveys (Modernel et al., 2018; Rossing et al., 2019), positive deviance approaches allowing a perspective from within farming communities. Long-term farmlet experiments allowed us not only to integrate scientific knowledge on animal physiology and plant–herbivore interactions in the redesign process but also to test for innovative and risky management options that would have led to unacceptable learning costs if tested on commercial farms. Some of these indeed failed, such as the *3x2* accelerated reproduction system with three lambings every 2 years under organic management (Benoit et al., 2009), and the splitting of mating into four seasons that increased workload (Benoit et al., 2014).

A key output from this case-study analysis is that while searching for multiperformance in grassland-based systems, it is essential to account for local and seasonal conditions so that the ecological and physiological processes to be optimized can provide the expected benefits (Bland and Bell, 2007; Ravetto Enri et al., 2017). A first illustration came from the herbage allowance manipulation experiments in Uruguayan Campos. In one of the farms, manipulation of herbage allowance could be made at a constant stocking rate (Do Carmo et al., 2018). On the other farm, primiparous cows grazed on shallow soils with limited water reserves, and it was mandatory to reduce the stocking rate so that improved aboveground sward productivity could increase cow energy intake during winter and BCS at calving (Claramunt et al., 2017). A second illustration came from the 3x2 accelerated reproduction system with three lambings every 2 years. While this practice is common and successful in conventional farms (see *3x2* in Benoit et al., 2019), high levels of concentrate consumption per ewe and higher lamb mortality strongly penalized this accelerated reproduction strategy under organic management (Benoit et al., 2009). Third, although an increase in self-sufficiency generally maximizes farmer profit, it could either result from (i) a drop in production costs that largely compensate for a slight or moderate decrease in milk or meat yield (Duru and Therond, 2015; *DT* system in Benoit et al., 2019) or (ii) technical gains enhancing production per animal and per hectare (Ruggia et al., in review). Different from a turn-key solution that would apply in all situations, searching for win–wins through the use of ecological processes in grazing systems thus calls for adjusting decisions to the local context and to production objectives. Such fine-tuning of grazing management is knowledge-intensive.

In analyzing these case studies, our goal was to question how researchers create actionable knowledge with farmers. We confirm the large scientific literature reviewed by Catalogna et al. (2018), who concluded that it would be more efficient to help farmers find their own solutions than searching for the best practices for large-scale transfer. For this, using social learning and collaboration approaches (Warner, 2006; Armitage et al., 2008) has a large potential to promote interactions between farmers and researchers. In Uruguay, scientific knowledge on cow reproduction physiology, plant growth, plant–herbivore interactions, and labor organization were used in a systemic way leading to a proposal of management options in the cow–calf system based on farm-specific diagnosis (Albicette et al., 2017; Ruggia et al., in review). Farmers adapted the proposals in action, with researchers supporting the processes by providing quantitative information on consequences and spaces for reflection. These reflection spaces involved regular exchanges between famers and project extension agents, as well as farmer group meetings to discuss changes in strategy. Further confidence building emerged from the involvement and enthusiasm of stakeholders operating at regional and national levels. These settings challenged some of the profound basic beliefs of farmers, including the benefits of high sheep-to-cattle ratios and attention dedicated to pasture management. Government and policy makers knowing about the project strategy and results considered it an inspiring approach for the implementation of policies. The current policy of extension services, however, does not support

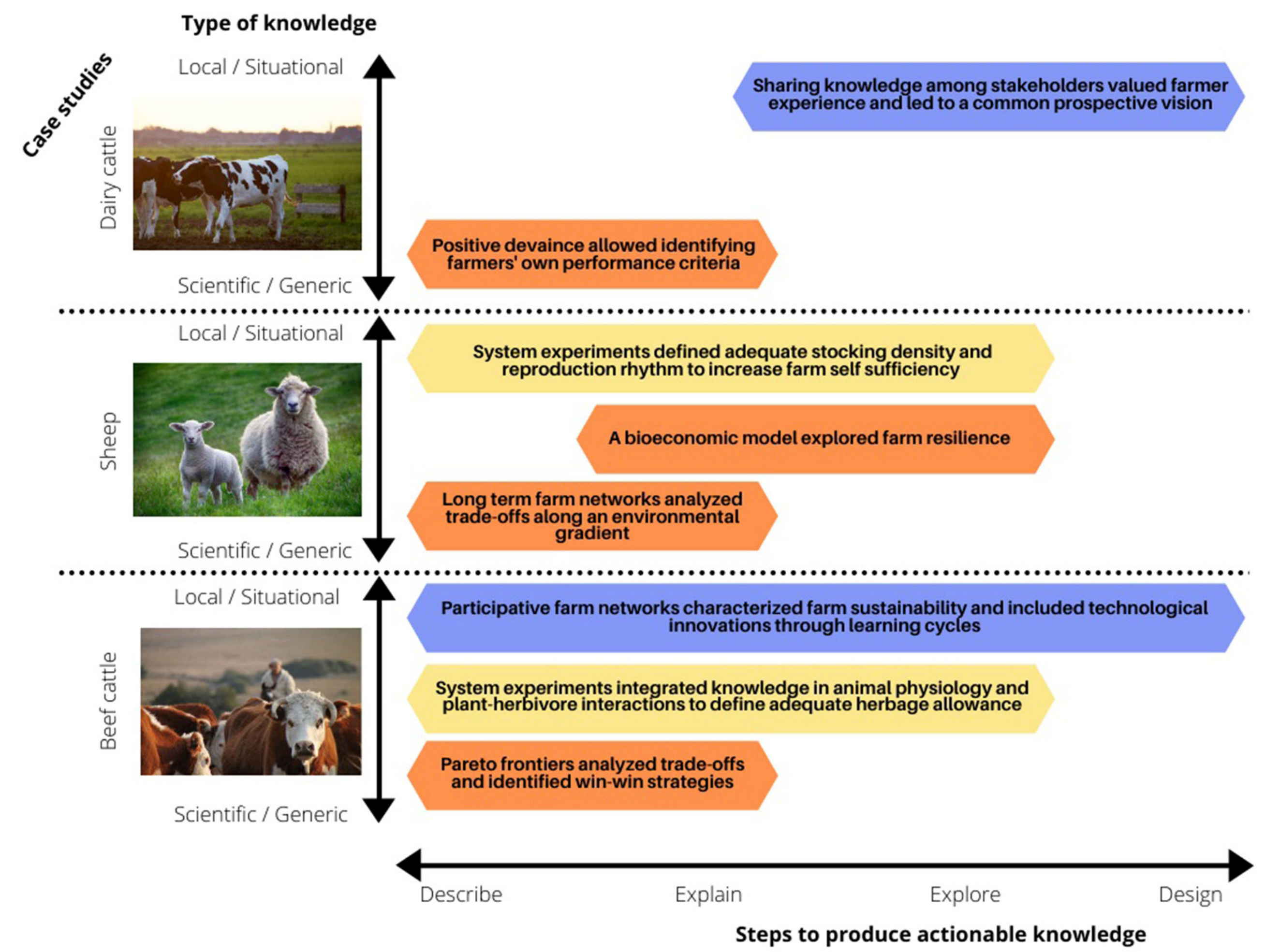

FIGURE 5 | In each production (dairy cattle, sheep, beef cattle), the different case studies from this article were reported along two axes according to the steps used to produce actionable knowledge (describe, explain, explore, design) on the X-axis and the type of knowledge that is being used (scientific—generic vs. local—situational) on the Y-axis. Box colors indicate the research approach: brown for trade-off analysis in farm network data, yellow for long-term system experiments, and blue for co-innovation.

this and rather subsidizes technical assistance around production programs focused on single products or outcomes.

In France, a crucial step in how farmers and researchers collaborated to formalize a common prospective vision for a PDO cheese area was the use of games that summarize the ecological and socioeconomic dimensions of livestock farming. Playing activity facilitated interactions as participants challenged each other's reasoning and conclusions in a safe environment despite their different and sometimes conflicting priorities and values (Dernat et al., in review). Participants taking the perspective of others more accurately were better able to explore different points of view (Johnson and Johnson, 2009) and to reach a common goal even if they did not have the answer individually. Playing allowed the discovery of unexplored options (e.g., switch to a full-hay diet) within the system and can facilitate appropriation by farmers of complex concepts such as ecosystem services. Emerging options promoted a more balanced portfolio of rural vitality and ecosystem services based on the valorization of the ecological and cultural value of local grasslands.

Crafting actionable knowledge in agricultural systems can be based on learning cycles, in which learning is conceived as a process resulting from the combination of system observation and diagnosis phases and transforming experience (Kolb, 1984; Kolb and Kolb, 2005; Cerf et al., 2012). Rossing et al. (in review) described their experiences with co-innovation and identified three dimensions of working: adoption of a complex system approach, creation of a social learning setting, and dynamic monitoring and evaluaton. In each of these dimensions, the research approaches described here provide support for systemically rethinking systems, whether to describe phenomena, explain them, explore alternatives, or select new designs for implementation (cf. Giller et al., 2008). Trade-off analyses are clearly focused on the "describe" (identifying outliers from Pareto frontiers or positive deviant approaches) and "explain" steps, while models allow the exploration of topics that are difficult to observe such as system resilience (**Figure 5**). System experiments allow to integrate scientific knowledge in the redesign process but are mainly focused on the "explain" and "explore" steps. Research that aimed to improve the sustainability of Uruguayan family farms through a co-innovation process accounted for the whole learning cycle, including the adoption of new technologies on the farms. Conversely, the focus was on farmer own experience rather than on the use of scientific knowledge in the French PDO cheese production area, researchers supporting the process by providing tools to facilitate collaboration between stakeholders. The last two case studies confirm the diversity of co-innovation approaches that aim to promote the development of agroecology (Lacombe et al., 2018). Overall, the greater the involvement of farmers as designers of their production system, the more informative the local and situational knowledge (**Figure 5**). Group learning and the structured co-innovation approach provided positive changes in grazing systems. Knowledge sharing between researchers, farmers, and other stakeholders allows the use of science-based analytical approaches and/or local knowledge in a systemic way and generates actionable knowledge to improve farm economic results while providing ecosystem services and various societal benefits.

ETHICS STATEMENT

Written informed consent was obtained from the individuals for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

BD, PM, MB, and WR conceived of the project idea and agreed on manuscript structure and case studies. BD, PM, MB, SDe, and WR reviewed the final version of the manuscript. All authors contributed to the article and approved the submitted version.

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Pursuing Plurality: Exploring the Synergies and Challenges of Knowledge Co-production in Multifunctional Landscape Design

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Knowledge co-production has emerged as an important conceptual and processual tool in sustainability research addressing the needs of equity and inclusion. Indigenous communities and local people have engaged with the process of knowledge production, foregrounding their historical relationships with landscapes, based on their unique worldviews and knowledges. However, knowledge co-production, especially for multi-functional landscapes remains a contentious and complicated affair with enduring issues of power-sharing related to the different socio-political positions of stakeholders. This work explores the synergies and challenges in knowledge co-production for landscape re-design in the south Island of Aotearoa NZ through an assessment of the work done at the Centre for Excellence, Lincoln University. At this center, a multi-stakeholder team is grappling with designing a farm, through a transdisciplinary framework that attempts to include multiple worldviews. This work explores the various stages of the co-production process, analyzing the exchanges between various members as they prepare for co-production, the knowledge produced through this engagement, and how this knowledge is being utilized to further the goal of sustainability. Our results show that significant gaps remain between co-production theory and co-production practice which are a result of the mismanagement of the co-production process, the mismatch in the time and spatial scales of project goals, and the differences in the values and objectives of the different stakeholders. However, the process of co-production, though flawed, leads to the building of more open relationships between the stakeholders, and leads to some very meaningful knowledge products that address the multi-temporal and multi-spatial aspirations of multi-functional landscapes in Aotearoa NZ, while contributing to the broader scholarship on co-production in sustainability. Finally, both synergies and challenges prove meaningful when challenging the roadblocks to the inclusion of a diversity of worldviews, by clearly highlighting the places of engagement and why they were made possible. We suggest that knowledge co-production attempts in multi-functional landscapes around the world should attempt a similar assessment of their process. This can help build better relationships between scientists and IPLC, address disciplinary bias and marginalization of non-expert opinions, while also ensuring the relevance of the research to the multiple stakeholders of the land.

Keywords: co-production, sustainability, multifunctional landscapes, indigenous knowledge, cultural mapping

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INTRODUCTION

The production, dissemination, and assessment of knowledge for sustainable landscape management needs to address the aspirations of a multitude of stakeholders and timeframes. While in the past such knowledge was biased toward certain academic disciplines, professions and institutions, in recent years there has been an opening up of this space, to reflect the plurality of aspirations, methods, and worldviews (Cornell et al., 2013). In international sustainability research, the idea of knowledge co-production has been deemed an important tool that addresses both the politics of knowledge production and argues for more democratic and hybrid forms of governance (Miller and Wyborn, 2020). But, knowledge co-production is a contentious affair, with probable points of divergence (and convergence) among the many producers with existing power imbalances (Fritz and Meinherz, 2020).

Knowledge co-production, according to a recent work by sustainability scholars which explores different strands of participatory and transdisciplinary research, should be "context-based, pluralistic, goal-oriented and interactive" (Norström et al., 2020, p. 183). Additionally, as decades of work done with indigenous people and local communities (IPLC) has revealed, any meaningful attempts at co-production must challenge universalizing and essentialist assumptions of contextual concepts like "sustainability," "vulnerability," "transformation," etc. (Parsons et al., 2016). It must also actively engage with decolonial methodologies which foreground inclusivity, ethics, and justice and advocate for reimagining historical accountability, responsibility, and the extraction of knowledge (Zanotti et al., 2020). Finally, recent work on co-production divides it into co-design, co-production and then co-dissemination and advocates for iterative and inclusive processes that attempt to wrestle with the plurality of knowledge systems, aspirations, and capacities (Tengö et al., 2017; Wyborn et al., 2019).

Knowledge Co-production for landscape design and management struggle with many of these considerations in the search for a process of collaborative stewardship which can facilitate power-sharing, negotiation, and conflict resolution (Cockburn et al., 2019). And, since landscapes are complex and dynamic entities that support a variety of processes simultaneously, their characterization as industrially planned monofunctional units, since the 1990s, has been replaced by the notion of multifunctionality (Cairol et al., 2009). This reflects the different aspirations of various stakeholders as well as the unique needs of place-based biotic and abiotic systems. The framing of multifunctionality, by integrating the production of ecosystem services with the management of sustainable production for human needs, also allows us to address the critical needs of human well-being, ecological health, and resilience in the face of increasing pressures of climate and land use (Fry, 2001; O'Farrell and Anderson, 2010).

While some scholarship has professed misgivings about multifunctional landscape design (Cairol et al., 2009; Knickel et al., 2009, 2018), others see great potential in it, especially when coupled with the emerging insights from knowledge co-production (Slotterback et al., 2016; Guzmán Ruiz et al., 2017; Duncan et al., 2020). Our work builds upon such considerations and explores the potential for multifunctional landscape re-design, which foregrounds knowledge co-production, to provide solutions to some of our vital social-ecological crises, sometimes referred to as "wicked" problems (Bornemann and Christen, 2020), while addressing the aspirations of multiple regional stakeholders. By assessing the process behind the work done at a transdisciplinary research collective at Lincoln University's Centre for Excellence focussed on Designing Future productive landscapes https://research.lincoln.ac.nz/our-research/faculties-research-centres/centre-of-excellence-future-productive-landscapes in Aotearoa New Zealand, we explore the process of co-production of knowledge.

While our work engages with recent scholarship on questioning Aotearoa NZ's colonial roots of landscape design (Abbott and Boyle, 2019; Marques et al., 2021) and trysts with multifunctionality (Pearson, 2020; Tran et al., 2020), it is deeply inspired by the powerful and ongoing mobilization the place-based cosmologies of the Māori people, the autochthonous/indigenous people of Aotearoa NZ (Lilley, 2018). Specifically, we work with the Mauriora Systems Framework (MSF) which is a processual framework emanating from Mātauranga Māori cosmology and Kaupapa Māori practice (Matunga et al., 2020).

Ultimately, guided by the two following research questions we explore the process of knowledge co-production in the re-design of a multi-functional landscape:

> *What are the major synergies and challenges that emerge during knowledge co-production when attempting to design and manage a multifunctional landscape in Aotearoa NZ?*
> *How do they challenge or support existing research on knowledge co-production for sustainability?*

This paper is organized in five sections below. In the first section, we present a literature review that examines some of the recent literature on multifunctional landscape design, knowledge co-production in sustainability, and Māori knowledge. In the next section, we provide an overview of our methods. We then present an overview of the project from Lincoln University, dividing the sections into co-design, co-production, and co-dissemination. In the fourth section, we answer our research questions, exploring the challenges faced during knowledge co-production, focussing on the major synergies and discords. We conclude the final section with an identification of the major limitations of our work and a vision for its future development.

LITERATURE REVIEW

Multifunctional Landscapes

Multifunctionality provides a useful prism for the planning and design of landscapes that are resilient to a variety of social-ecological challenges and address the aspirations of a wide variety of stakeholders (Cockburn et al., 2019). Multifunctional landscapes emerge as spaces that address the needs of agricultural production while enhancing vital ecosystem services and serving multiple institutional needs (Song et al., 2020). Additionally, due to the multiple scales that populate landscapes it also helps knowledge producers and managers deal with the limitations of the farm, city, or region. Ultimately, multifunctional land use ushers in new institutional arrangements and new relationships between knowledge producers and managers which biases more horizontal and lateral connections instead of vertical ones. In re-imagining these linkages there is also a significant degree of spatialization that is infused into our knowledge and management practices (Wilson, 2009; Slotterback et al., 2016; Cockburn et al., 2018).

The opening up of the planning and design space to such plurality of aspirations and discourses brings with it significant concerns around the management of such diversity to ensure the objectives of the overarching landscape plan (Pinto-Correia et al., 2019). While in the past this plurality was managed through a productivist, economic lens, mirroring cost-benefit negotiations between different monetary evaluations of the land (Yoshida, 2001; Cairol et al., 2009), in recent years, such thinking has been challenged by a more holistic perspective that pursues social-ecological well-being through synergies across economic, ecological and cultural goals (Spataru et al., 2020). Such framings have received further support due to the various manifestations of the Anthropocene and its current and probable future impacts on our agricultural systems (Gorman et al., 2020). Additionally, recognizing the different subject positions occupied by different stakeholders and the varying amounts of power they represent, are seen as vital in understanding the decision-making pathways of multifunctional land use (Duncan et al., 2020; Fagerholm et al., 2020; Jackson et al., 2021). Such an understanding has highlighted the need for pursuing collaborative landscape stewardship in multifunctional landscapes and the lack of qualitative, place-based literature on the factors influencing such collaboration in contentious contexts (Cockburn et al., 2019).

In Aotearoa NZ, akin to other settler colonies, land management is a contentious issue (Te et al., 2019; Ojong, 2020). In recent years there has been a recognition within the literature of the historically ongoing resistance by indigenous communities, the Māori, to colonial and industrial visions of landscape design and management (Marques et al., 2018; Abbott and Boyle, 2019). Māori communities and scholars have instead proposed landscape design and management rooted in their culturally derived worldview and knowledge system, *mātauranga* Māori, which foregrounds *whakapapa*, a genealogical web that connects humans to the non-human world (Harmsworth et al., 2016; Spiller et al., 2020). Therefore, the valid inclusion of the *mātauranga taiao* (Māori environmental knowledge) and the *mātauranga-a-iwi* (place-based knowledge of individual tribes) to inform the *tikanga* (cultural protocols and habits) required for the production of knowledge, is at the forefront of Māori concerns about land stewardship and sustainability (Stevens et al., 2016; Kitson et al., 2018; Wilkinson et al., 2020).

Knowledge Co-production in Sustainability Science

Knowledge co-production in the arena of sustainability science, natural resource management, climate change, and other areas of policy focussed research has emerged as a response to the complexity and dynamism of our social-ecological systems, the challenge from different social actors regarding their lack of representation in reductionist knowledge frameworks and to ensure that decision-making pathways are equitable increasing the potential for operationalization of the knowledge produced (Grove et al., 2015; Galvin et al., 2016; Muccione et al., 2019). The roots of co-production are rooted in methods and concepts like participatory action research, transdisciplinary research, postnormal science, and civic science, whose overarching goals are the creation of iterative and inclusive processes, which allow for the development of common ground and trust while building new capacities to address complex problems and ultimately, enhancing the usability of scientific information beyond the academy (Wyborn et al., 2019).

While advocates for co-production tout its various benefits, there is a significant critique of the process, which highlight the troubles with finding the common vocabulary to define objectives and goals, the enduring legacies of power that destabilize and depoliticize, the struggles with sustaining co-production beyond the initial co-design phase and the decay of trust due to the inability of institutions to address the emerging transformative conclusions (Lemos et al., 2018; Turnhout et al., 2020). Therefore, co-production is not a silver bullet panacea, and there remain significant issues in understanding how long-term co-production can be sustained and the problems that arise when transitioning from co-production theory to co-production practice (Jagannathan et al., 2020).

The practice of co-production is often the focus in projects involving indigenous communities (Tengö et al., 2017; Hill et al., 2020; Zanotti et al., 2020; Wyborn et al., 2021). In recent years multi-scalar research initiatives such as the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), Convention on Biological Diversity (CBD), and the Intergovernmental Panel on Climate Change (IPCC) have all attempted to engage with various instances of co-production with indigenous and local knowledge (ILK) to varying degrees of success (Ford et al., 2016; Tengö et al., 2017; Schröter et al., 2020). Additionally, more place-based initiatives have also been attempted, often concerning climate adaptation, conservation, urban planning, natural resource management, and extractive industrial development planning (Bezner Kerr et al., 2018; Mazzocchi, 2018; Persson et al., 2018; Reiter, 2018; Upton, 2019; Lauter, 2020).

In Aotearoa NZ there have been similar mobilizations over the past decade, often using juridical mandates enshrined in the bicultural goals of the nation, especially the Treaty of Waitangi (Dominy, 1990; Garner, 2017; Morgan et al., 2019). In the process, Māori scholars and communities have challenged the "ongoing privileging of one knowledge system and suppression of the other" and questioned knowledge production objectives that don't actively pursue a policy of matauranga revitalization in support of Māori self-determination and rights (Bishop, 1999; Leonie et al., 2002; Broughton and McBreen, 2015). This robust culture of seeking knowledge equity as an inseparable component of cultural well-being has led to the creation of multiple approaches, tools, and frameworks that center *mātauranga* and

TABLE 1 | Breakdown of the different goals, methods, and stakeholders of the teams within the COE.

Team	Goals	Methods/tools	External stakeholders
Social	To gauge interest within the regional farmers for incorporating the redesigns being proposed by COE and to ascertain current anxieties and aspirations of farmers	Semi-structured interviews, surveys, literature review of current literature	Farmer collectives, primary industry organizations, Beef/Lamb/wool producer groups
Pastoral Production/Landscape Health	To redesign a pastoral landscape that enhances pastoral livestock production while addressing ecosystem service needs of the land	Place-based biophysical data collected on-site, LIDAR data, land use/land cover data from the national database (LINZ)	Remote sensing and digital analytics companies, Natural Resource management collectives, Agroecological evaluation companies
Te ao Māori	To redesign an agricultural landscape using the principles of mauri enhancement and by tracing a historical genealogy of land use and ownership	Maori cultural mapping using the MSF framework, using base maps from *Kā Huru Manu*, The Ngāi Tahu mapping project	Various regional maori *iwi*, Ka huru Manu, *Papatipu Rūnangas*
Design	To create farm-scale design plans by engaging with multi-stakeholder aspirations and transdisciplinary data sets	GIS data, spatial analysis, design thinking, landscape architectural methodology	Farm managers, data visualization and analytics institutions, primary industry

kaupapa Māori (Marks, 2015; Lilley, 2018; Stevens et al., 2020). One such tool is the Mauriora Systems Framework (MSF), which was developed to support cultural responsible environmental decision making by delineating the four pieces which create environmental decision making: *Taonga* (material and more-than-material resources of value), *Tikanga* (cultural practices and actions), *Kaitiaki* (stewards and decision-makers), and *Mauri* (the life force that is inherent in all living beings. The MSF initially developed in the 1990s, was to ensure that Māori spiritual and cultural values were recognized in evaluation attempts and that place-based Māori community interests were represented in various aspects of land and environmental knowledge production and governance. The MSF is centered on the idea of *mauri*, which is the lifeforce that is within all living things and joins all the elements in the world, creating a holism. The frameworks' primary objective is to protect, maintain and enhance the mauri of the system, as considered to be valid by *kaitiaki*, consistent with the *tikanga*, to achieve a state of *mauriora*: well-being (Matunga et al., 2020). The way this framework functions is that an external proposition (science/governance-related plan, policy, project, etc.) activates the system. The scope of the proposal helps inform who specifically within the Māori community will be impacted by this. Once the stakeholders have been identified, their *kaitiaki* evaluate the plan concerning their *tikanga* and explore possible effects to the mauri of their *taonga* (tangible and intangible objects of value). This evaluation forms the foundation of their engagement with the process (Matunga et al., 2020). The MSF rooted in *te ao* Māori (Māori worldview) grants autonomy and control to Māori communities over management, planning, and knowledge production practices which allow the Māori as a historically marginalized IPLC to assert their opinion on a plethora of issues.

Ultimately, such questions of autonomy, sovereignty, and marginalization remain unresolved in much of co-production research (Turnhout et al., 2020). Scholars and practitioners have suggested different reasons for this, however, there is also an identified need to engage with the existing principles of knowledge co-production and identify not just moments of synergy and success, but also divergences, challenges, failures, tensions, and trade-offs (Polk, 2015; Wyborn et al., 2019; Norström et al., 2020). Such an undertaking can help reveal the limits of our methods while identifying the mismatches between our ideological goals and the functional (and institutional) capacity for such conclusions to be operationalized.

METHODS

Situating the Study

The corresponding author of this paper (RC) was a post-doctoral fellow hired by the COE in 2019 to work on qualitative data collection, engagement with farmers, and to assess the process of knowledge co-production being attempted. Different groups were set up within the COE to focus on the different disciplinary aspirations and the different thematic needs. Broadly defined there were four teams: *the social team, the pastoral production and landscape health team, the te ao Māori team, and the design team*. The team goals within the broader umbrella of the center were given in **Table 1**.

RC was a part of the social team as well as the Māori team and distributed his time between doing in-depth literature reviews, collecting qualitative social data through interviews with regional farmers, conducting ethnographic participatory observation during the various meetings of the COE, and working with other members of the Māori team produce cultural maps and collaborative maps. The transdisciplinary and multi-stakeholder team, which was created at the COE at Lincoln University, over the last 2 years, has been engaging with some critical issues related to exploring and designing multifunctional landscapes in Aotearoa NZ. The objectives of the center are to transform existing landscape management practices through multi-functional landscape design that incorporates systems thinking, landscape ecological principles, and *mātauranga* Māori

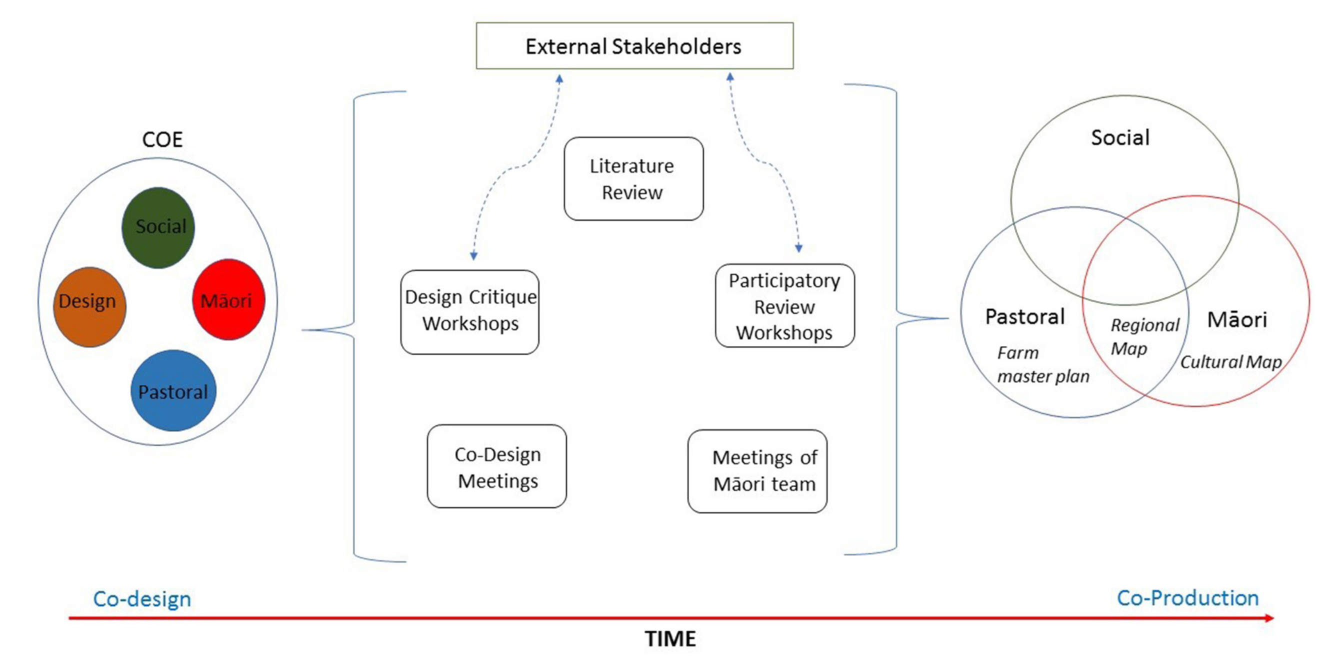


FIGURE 1 | Diagram showing various parts of knowledge co-production at the COE.

knowledge. Additionally, to explore these questions the COE has attempted to pursue a process of co-production. However, this vision is a product of various institutional realities of the small, land focused university it is embedded within, the politics of the primary production and land management industry in Aotearoa NZ, ongoing negotiations between Māori and the state regarding their historical claims and the impacts of the Covid-19 pandemic. For example, the knowledge co-production process we discuss in this paper is for the re-design of a farm located in the high country of the South Island of Aotearoa NZ. Mt. Grand station is a Lincoln University-owned high country sheep farm located in the upper Clutha basin in Central Otago (https://www.topomap.co.nz/NZTopoMap/nz21374/Mount-Grand/). The past and the future of the region this farm is in elicits very different aspirations from different stakeholders. For the descendants of European farmers who colonized this land, it is a generational transfer of both culture and wealth of which they are fiercely protective (Swaffield and Brower, 2009). On the other hand, for the indigenous Māori, the high country is unceded, stolen land, which was taken by the colonial state through institutional trickery and whose social-ecological systems have been exploited and ruined by colonial land management. The reclaiming of this land under indigenous stewardship is a key part of Māori sovereignty claims in current day Aotearoa NZ (Yates, 2021). Such contentions were (and are) in the foreground of discussions within the COE regarding the future of the farm as a multi-functional landscape. This data for this paper reflects these deliberations.

Within the COE, the scholar leading the Māori team is a member of the Māori *iwi* (tribe), whose historical territory and current land claims the farm in question sits within. Additionally, he also has close relations with the *iwi* whose land the university is situated on. Given these socio-political ties to the involved indigenous stakeholders, the Māori team was given access to spatial and cultural data which were instrumental in the building of the cultural maps. This access to the regional *iwi* data was given only to the Māori team and therefore, it was only the final maps that were brought to the bigger COE collective. Ultimately, the usability of the produced maps was seen to be a vital reason for this access, given the ongoing negotiations between the Māori and the colonial state through the Treaty of Waitangi (Te et al., 2019).

Data Collection

The data for this paper was gathered through a mixed-methods toolkit which consisted of mining literature on knowledge co-production to identify salient features of such process from attempts across the world; semi-structured interviews with some regional farmers; ethnographic participatory observation during group meetings at the COE and also during specific thematic group meetings; and ethnographic participatory observations during multi-stakeholder design critique workshops and participatory review workshops (**Figure 1**).

The data collected for this paper does not reflect the full array of methods utilized at the COE by the various teams to perform their tasks. Instead, the data collection methods mentioned in **Table 2** address the question of assessing the knowledge co-production at the COE as mentioned before.

TABLE 2 | Mixed-methods data analyzed for this paper.

No.	Name	Number	Definition	Objective
1	Literature review for guiding stage 1 of Co-design (section Stage 1 of Co-design)	30 peer-reviewed journal articles/book chapters	We conducted a systematic review of literature emerging from different disciplines with a focus on more recent (2000–2021) scholarship on knowledge co-production in sustainability and environmental/land management with a focus on projects that attempt IPLC collaboration	To ascertain the state of current scholarship and to identify key concepts/tools of knowledge co-production
2	Co-Design Meetings held at the COE which inform the Stage 1 and 2 of the Co-design process (sections Stage 1 of Co-design, Stage 2 of Co-design)	20 (These varied in number from 5 to 16 people per session)	These were structured and semi-structured meetings often moderated by 1–3 people, held in conference rooms on the Lincoln campus. These were attended by faculty affiliated with the COE, primary industry collaborators, designers, and other stakeholders	To foster transdisciplinarity through collaborative discussions about values, goals, objectives and to proceed with the redesign of farms using a multifunctional, multistakeholder framework
3	Participatory review workshops	2 (These included 9 in one setting and 16 in another)	These workshops which involved engaging with stakeholders with place-based knowledge about the land we were attempting to redesign were used to create a set of topics and sub-topics that were of importance for the social-ecological well-being. These workshops used strategies from participatory research (Fazey et al., 2020)	To engage with stakeholders beyond the COE to gather their opinions about whether the research goals and design objectives of the COE addressed important current and future regional issues
4	Semi-structured interviews with primary producers	7 (A lot more of these were planned but had to be abandoned due to COVID-19 related complications)	These interviews were with different farmers (dairy, mixed crop, sheep, and beef) and were conducted at their homes, on Lincoln campus, at the farm, and over the phone. They were covered by the requisite Institutional Review Board approval for research with human subjects.	To engage with individuals and communities engaged in primary production to understand their opinion about the work being developed at the COE and their aspirations/anxieties about their livelihood
5	Design critique workshops	2 (One of these was attended by community stakeholders and the other was for university administrators)	These were discussion-group driven events, which were moderated by 1–3 members of the COE, and were to collect opinions on ongoing efforts of the COE, and were held at a high country station (sheep/deer farm) and on the university campus.	To engage with primary industry stakeholders, natural resource managers, and university administrators to solicit their opinions about our initial redesign attempts for the farms
6	Meetings of the te ao Māori team	12 (These were attended by the 3–5 people who were directly involved with the Māori theme of the COE)	These were meetings held on the Lincoln University campus and in and around Lincoln town to work on realizing goals, objectives, and eventually methodologies to complete the work.	To come up with a strategy that would allow for the successful completion of the cultural mapping project, provide spatial connections with the farm-scale mapping and create a tangible product to take to regional iwi for critique

Data Analysis

The analysis of data for this paper was done in three separate ways. First, the knowledge production literature that was reviewed was mined for conceptual insights which could help guide the COE's creation of a process for knowledge co-production. These insights were then used by COE members as starting points for discussions around how to perform contextual knowledge production in the specific context of the

COE, the region where the farm was located, and financial and temporal constraints.

Second, ethnographic participant observation notes (Yang and Gilbert, 2008; Kansanga and Luginaah, 2019) were taken at the co-design meetings, design critique workshops, and participatory review workshops and meetings of the Māori team. These were transcribed and qualitative coding was done followed by thematic coding in two rounds (Nowell et al., 2017; Matuk et al., 2020). The first round identified important thematic categories and helped situate the data within the four most prominent themes: *values, inclusion, methods, and engagement*. Conversations of values focussed on more abstract ideas of what the project was about and what our goals were and explored questions of accountability and equality. Conversations of methods focussed narrowly on the how what and why of the different tools that we were using to address the question at hand. Conversations of inclusion focussed on the involvement of stakeholders beyond the academy, while conversations of engagement explored how different disciplinary and epistemic collaborations (and dialogue) could be facilitated within the group, while in a way this could be seen as a sub-set of methods, it emerged as its category given the importance it was given during our process and our overarching goal of collaborative knowledge production. In the second round, we probed more into, what we defined as, moments of *synergy* and *challenge* during the meetings. Synergy was defined as an exchange where the speakers agreed and added to each other's opinion while a challenge was an instance where an opinion was challenged, and the exchange ended with a resolution. We mined the data for such exchanges and summed them up by the teams the individuals belonged to. The individuals engaged in these exchanges were tagged by their affiliations to the four intra-COE teams.

Third, the knowledge products that came out of the co-production process at the COE were contextualized by presenting the specific aspirations and ultimately the transdisciplinary and multi-stakeholder process, which they emerged from.

RESULTS

The results of the knowledge co-production process can be divided into two main parts. The first explores synergies, challenges, and learning outcomes from the process of knowledge production which responds to the overarching exploration of knowledge co-production in sustainability research which is the central objective of this paper. We also present certain knowledge products in a second part which are the conceptual artifacts that emerged from this process. Since the goal of this paper is to *assess the process of knowledge co-production* and not simply to present products from the co-production process, the relevant methods used to create such products (cultural mapping, spatial landscape design) are not explored in detail as part of the overall methods of this paper. Therefore, the results presented below are the ones that explore the process of production of knowledge itself within the COE, with some relevant knowledge products presented as emerging conceptual and material conclusions from such knowledge-coproduction.

Synergies, Challenges, and Learning Outcomes From the Knowledge Co-production Process

During this initial phase, the framing of projects was significantly disciplinarily biased, with individual teams suggesting overarching objectives, and the co-defining of the problem space was restricted to the very abstract. While logistical matters surrounding project goals, delivery dates, and probable methodologies were rigid and inelastic within each team, there was a dialogic progression toward more perforated objectives and tools. This process emerged through design meetings held at the COE from *August 2019* to *March 2020*. These meetings were recorded, minutes were taken, and detailed notes compiled. This stage of knowledge co-production is termed Co-design.

In the next few sections, we explore the co-design meetings to categorize the conversation under the four themes mentioned before and to highlight moments of synergy and challenge which emerged during the process. Additionally, we also explore certain key activities undertaken by the specific teams during these stages of the process.

Stage 1 of Co-design

The two stages division of the Co-Design process emerged from the clear demarcation between the initial stage when discussions centered on goals and objectives of the project vs. the second stage which proceeded from a more concrete organization of capacities, actors, and goals that the COE wanted to pursue.

During stage 1 of the Co-design, a literature review was compiled from which certain important and useful concepts were identified (**Table 3**). This was done to situate the work being attempted at the COE in the broader scholarship and methods of co-production and to identify relevant ideas which could be explored in the regional context of Aotearoa NZ.

Using insights from the scholarships presented in **Table 3**, through the process of co-design meetings, we decided upon the following salient features (**Figure 2**).

These salient features attempted to capture the diverse aspirations of the group within a few guiding ideas. Plurality was nominated to encompass the needs of transdisciplinarity but also address the IPLC knowledges which did not neatly fit within the expert-driven knowledge systems of the university. Accountability and Māori Self Determination were both nominated to address the historically exploitative relationships between scientific practitioners and Māori communities and to safeguard knowledge diversity and usability within the projects (Tengö et al., 2017). Finally, Multi-Faceted goal-setting and Contextual Engagement and Integration were nominated to ensure that the process remained aware of the temporal and financial constraints while facilitating multi-stakeholder engagement which was more than mere tokenism (**Figure 3**).

Important Outcomes

- While it was deemed vital to engage with Māori and regional farmers more intimately during the early design process, relevant stakeholders noted the burden this would represent. Especially given existing engagements between such groups and academic projects. It was decided that the initial co-design

TABLE 3 | Identifying guiding principles and goals for knowledge co-production.

No.	References	Concepts/tools
1	Wyborn et al., 2019	• Recommendations for the Co-production process • *Preparing for co-production*: During this early phase, • Ensure representation from all relevant stakeholders with attention to culturally important entities and typically marginalized communities • Carefully select a facilitator for the process • Create relationships between horizontal actors • Consider venue and meeting materials and be explicit about the decision-making process, highlighting responsibility, accountability, and sharing • *Managing co-production:* During this phase, • Ensure openness and flexibility • Focus on broad, cross-cutting issues • Carefully consider power dynamics • Facilitate capacity building • *Sustaining co-production*: To ensure the long term viability, • Establish non-exploitative and non-extractive relationships between actors • Explore options beyond the budgetary constraints of current work • Focus on pre-existing institutional context and identify relevant scales that can be explored further
2	Norström et al., 2020	• Principles for Co-production in sustainability research • *Context-Based*: Situate the process in place-based realities • *Pluralistic*: Directly and advertently recognize the multiple ways of knowing and doing • *Goal-Oriented*: Articulate clear goals that are shared, meaningful and achievable • *Interactive*: Facilitate ongoing learning among the different stakeholders through different engagements
3	Polk, 2015	• Challenges for transdisciplinary co-production • *Capturing Multiple Framings*: Address through joint problem formulation and design • *Integrating knowledge diversity*: Address through co-generation of data, joint analysis, and implementation • *Evaluate*: Address through formal evaluations of processes and impacts
4	Jagannathan et al., 2020	• Outcomes from Co-production should be divided into, • *Scope 1 outcomes*: These center around benefits from the production and dissemination of decision-relevant knowledge and services • *Scope 2 outcomes:* These are more ambitious and may transform societal power structures and political systems and re-order science-society relationships • While Scope 1 outputs are easier to measure and document, it is often the Scope 2 outcomes that are harder to achieve but are often being pursued as the end goal for co-production.
5	Broughton and McBreen, 2015; Wilkinson et al., 2020	• Knowledge co-production with Māori communities and actors must, • Recognize *tino rangatiratanga* and self-determination of the Māori • Include restoration of the material and cultural systems and artifacts • Prioritize projects that are most likely to support *hapu* and *iwi* to develop and practice *matauranga* • Identify mutual research needs and benefits • Identify potential challenges and risks of researching the cultural interface

process would be decided by a core group of COE members with input from regional stakeholders once the overarching objective of this work was more concrete.

- The team was split into various smaller groups, with theme leaders, decided by disciplinary/epistemic/ideological boundaries. This decision reflected the early aspirations of an expert-driven, tentatively co-produced design which was iteratively transformed through dialogue toward a more plural knowledge framework, foregrounding mātauranga Māori sovereignty.
- While questions of "value" were the most contested and challenging, they were often tabled, given the constraints of time, and the group was corralled by theme leaders toward questions of method and probable outputs.
- The tools of GIS, spatial analysis, and Geo-design emerged as a powerful knowledge production and management tool during these early conversations. This presence of a potential favored tool kit also catalyzed the creation of different groups within the COE team. It was decided during this time, to use the framing of different ontologies, cosmologies or worldviews, and different epistemologies to divide the COE methodology into the constituent, relational, and *Te ao* Māori analytical pathways. The worldviews described as Relational, Constituent, and *Te ao* Māori, relate, respectively, to ontological differences between the critical social sciences/humanities, positivist science, and indigenous knowledge. Therefore, the relational worldview is guided by theoretical insights from constructivism, post-humanism, post-materialism, post-modernism (among others), that question the reality of human-nature binaries, while imagining how entangled relationships between different subjects and processes exist at material and more-than-material levels (Whatmore, 2006; Castree, 2015; Rocheleau, 2016). The constituent worldview is rooted in the positivist ontology which often claims (with some caveats) that truth and reality are free and independent of the viewer and observer and can be understood through repetitive experimentation which quantitatively adds up the sum of all the parts. Much of natural and physical science research is embedded in this paradigm which often seems quite oppositional to the relational worldview (Patterson and Williams, 1998; Meissner, 2016; Ely et al., 2020). Finally, the *Te ao* Māori worldview represents place-based indigenous engagements with various aspects of reality (as mentioned before).

Stage 2 of Co-design

Stage 2 of Co-Design proceeded with an identification of the technical and the manpower capacities of within and across the different teams of the COE, driven by the overarching conversations from stage 1 of Co-Design (**Figure 4**).

Important Outcomes

- The second stage of the Co-design process consisted of a lot more conversations around the inclusion of other stakeholders and a move toward exploring knowledge co-production. However, despite this objective, most of the focus remained on finalizing the methodology for the work, without much focus

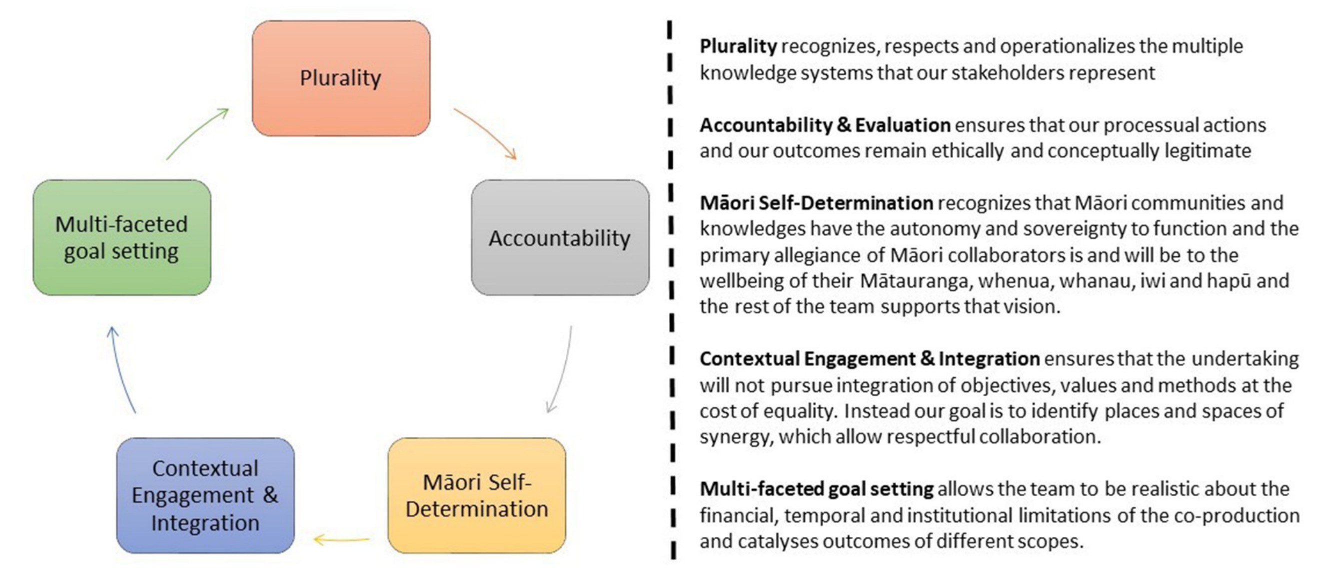


FIGURE 2 | The Salient features driving our co-production process at the COE.

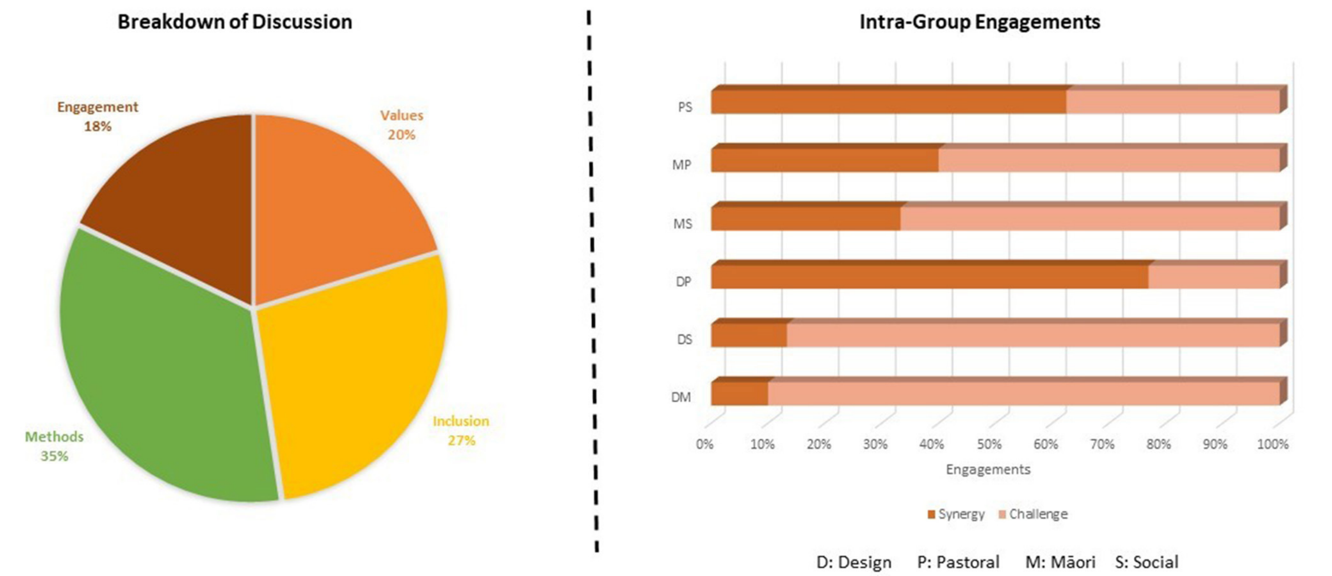


FIGURE 3 | Stage 1 of Co-Design Meetings (The Intra-Group engagements graph only represents coupled engagements such as DM or PS. However, there were many multiple team engagements, such as DMS or SMP. These are currently being analyzed and will be used in future publications).

on how the transdisciplinary engagement across different internal teams would be facilitated and managed.

- While there was some discussion about more rooted values, the group seemed to have settled on a set of values which while not without contestation in its entirety, allowed for the project to move ahead.
- As the COVID-19 pandemic was beginning to show up on the group's radar certain decisions were taken regarding the empirical data to be collected from various stakeholders. These decisions pushed the project toward more desk research and moved research funding toward top-down remote sensing products.
- The COE also spent a significant amount of time in this second stage engaging with various institutional stakeholders, many of which were part of the primary production industry. This was driven by a need to secure funding to ensure the sustainability of the COE, but also to create relationships with institutions and actors who could help critique the functional potential of multi-functional landscape redesign projects.

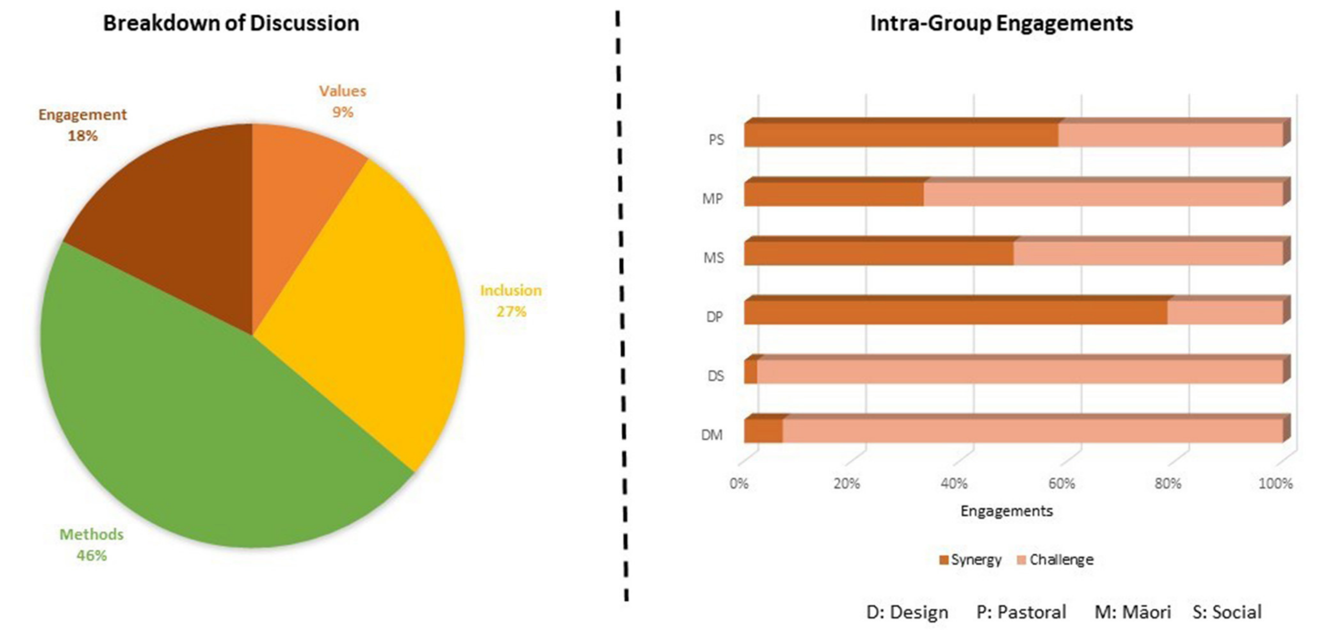


FIGURE 4 | Stage 2 of Co-Design Meetings (The Intra-Group engagements graph only represents coupled engagements such as DM or PS. However, there were many multiple team engagements, such as DMS or SMP. These are currently being analyzed and will be used in future publications).

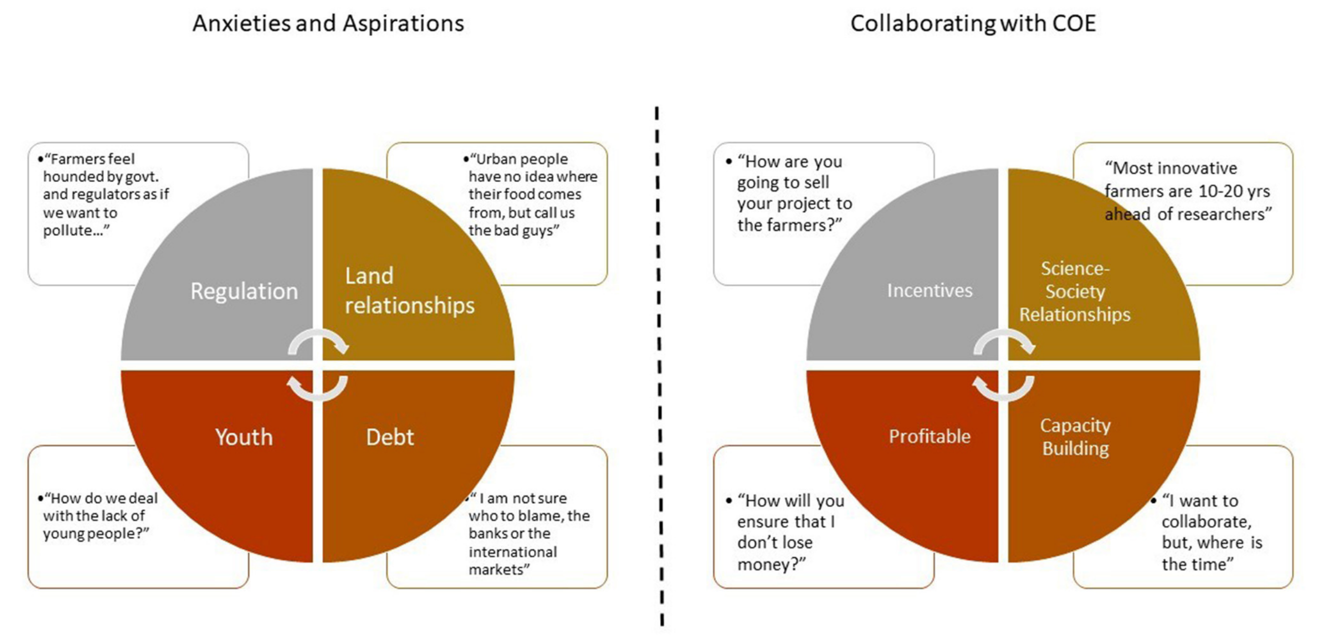


FIGURE 5 | Farmer opinions: emerging themes with representative direct quotes.

Key Activities Undertaken by Different Teams During the Co-design Process

The Social Team

Despite the significant effects of COVID-19, both on the livelihoods of primary producers in Aotearoa NZ and the constraints it put on more intimate engagement with such stakeholders, the social team did manage to get some information about the aspirations of regional farmers and industry actors. These are presented below.

Farmer Opinions. The COE team conducted semi-structured interviews with 7 people involved in the primary production industry from the South Island. Of the 7 there were five men and 2 women, and 2 were involved more in the industry with the supply chains of primary production and 5 were primary producers who were farming sheep, beef, and dairy.

They were asked questions regarding,

(1) Their current anxieties and aspirations?

(2) Their future anxieties and aspirations?

(3) What did they think about the COE and the work being attempted there?

(4) Would they want to be a part of such work? Why or Why not?

(5) Did they have any advice for us?

The anxieties and aspirations of the primary producers echo recent research into rurality and livelihoods in Aotearoa NZ (**Figure 5**) (Lewis et al., 2013; Rosin et al., 2017).

Their answers to work being done at COE and potential avenues for collaboration were heavily concentrated on incentives and the lack of capacity to engage. All 7 agreed that there needed to be more collaborative work across science-society, especially through initiatives that did not position the knowledge of the scientists as more important than the knowledge of the farmers.

The Te ao Māori Team

Māori Cultural Mapping. The team working on Māori cultural mapping decided on three objectives to pursue through their work with the COE.

- To use Māori cultural mapping as a tool to re-imagine and re-design the landscape. To aid in this process they reached out to *Kā Huru Manu*, The Ngāi Tahu Cultural Mapping Project (https://www.kahurumanu.co.nz/) to procure existing cultural landscape visualizations, which would form the foundation of their mapping activities.
- To use the Mauriora Systems Framework (MSF) (**Figure 6**) both as a processual tool to ensure Māori knowledge sovereignty and as a conceptual tool to understand the present state of the mauri and how to ensure its well-being in the future under various landscape management scenarios.
- To accept that there is incredible demand on Māori *whanau*, *iwi,* and *hapu* to participate in decision making and knowledge production on such projects. Keeping this in mind, the formal opinions and time of the *kaitiaki* would be requested judiciously and the Māori team leader would informally engage with them regularly to inform them of the team's ongoing work and ask them for feedback.

The Design Team

Participatory Objective and Goal Setting. The COE during Stage 2 of the Co-design also facilitated multiple workshops to engage different stakeholders in the process of critiquing and suggesting landscape management objectives for the re-design project. These opinions were focused on the pastoral production and ecological health aspects of the landscape.

We used a participatory weighting technique, inspired by participatory action research (Farr, 2018; Johansson and Abdi, 2020) which quantified stakeholder aspirations by gauging both their self-described prowess about a topic and the collective expertise of the group. The results are shown in **Figure 7**.

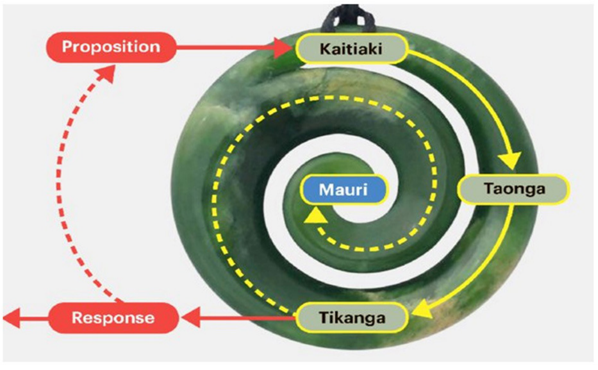


FIGURE 6 | The Mauriora Systems Framework.

Water quality, agroforestry, and pest management were identified as the three issues that were not being addressed by current practice which needed significant focus in any future re-design attempts. Interestingly while pasture-based production systems were being addressed in the current scenario the need to ensure their well-being in future landscape design was quite robust.

The Pastoral Production and Landscape Health

Farm Scale Spatial Mapping. The team identified existing farm-scale data from the national land use and land cover database which is used in conjunction with LIDAR data produced by data analytics company and field data gathered on-site at the farm to create capability and suitability maps using ArcGIS software (**Figure 8**).

Overview of Co-design

- Co-design at the COE was a contentious and dynamic process with processual objectives changing based on discussions and engagement within the group. The salient features of the co-production process mentioned in **Figure 1** did not emerge linearly at the beginning but instead were developed throughout the co-design process.
- The COE group spent the most amount of time discussing methods, while values and engagement were the least discussed (**Figures 3**, **4**).
- The most synergy was seen between the design team and the pastoral team, while the most challenging exchanges happened between the design team and the *te ao* Māori and the social teams (**Figures 3**, **4**).
- While the opinions of stakeholders from the primary production industry are quite insightful their engagement with the overall co-design process was quite minimal (**Figures 5**, **7**).

Knowledge Products From the Co-production Process

Knowledge co-production at the COE took the main stage starting in March 2020 and that process is ongoing. The co-production through the various teams and the COE given the capacity (technological and labor), skill sets, funding timelines,

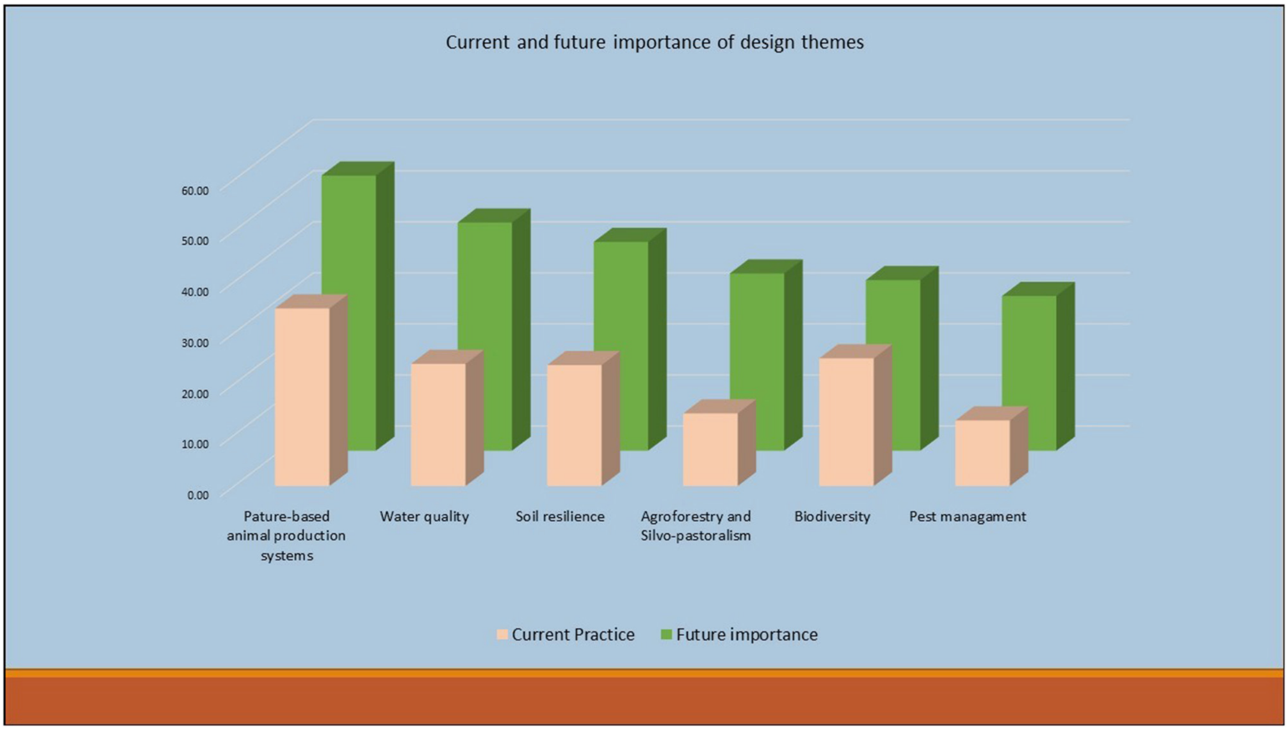


FIGURE 7 | Results of participatory opinions on COE design themes for landscape re-design ($n = 25$).

institutional mandates, and long/short term goals led to a culture of co-production which is visualized in **Figure 9**.

From the figure above it can be surmised that the process of co-production echoes the synergies and challenges that emerged during the co-design process and contain both "strong" moments of co-production (MD, SD, MS) and "weak" moments of co-production (M, S, D). The most advanced knowledge products are the ones associated with Māori and Pastoral and Design. In the next few paragraphs, we summarize some of this work to present some tangible outcomes of the knowledge co-production process.

D: Farm Scale Master Planning

The farm-scale master planning was done using existing land use and land cover data, farm management plans of MT. Grand, site visits for ecological and hydrological mapping, remotely sensed products, and stakeholder insights that emerged from co-design workshops and participatory review of design goals and themes. It also considered the existing capability and suitability of the landscape's production management and incorporated some of the insights from regional primary producers and industry actors. A tentative draft master plan is shown in **Figure 10**.

The plan as it currently stands focuses on regenerative silvopastoralism, soil resilience, hydrological management, and the creation of a carbon positive landscape. This plan is a result of collaborative efforts within the design and pastoral teams with complementary inputs from the social and Māori teams.

The tools highlighted in this knowledge product are GIS-based spatial analysis, landscape ecology design principles, and farm management planning and the scale of focus is the farm. In detail, the process entailed,

- Multi-objective ecological and production-related aspirations for the farm were obtained from managers and scientists. These included the capability of the land to support healthy pasture, soil management, and soil management, enriching riparian buffers, changing rabbit habitats, and improving biodiversity through Silvo-pastoral systems.
- Remote sensed data products, existing land cover maps, farm management plans, and regional zoning maps were brought together to situate the farm within a certain spatial context and to identify areas of special vulnerability.
- Paddock scale SWOT analysis of the complete station done by the various experts that are part of the center. This analysis took into consideration the disaggregated objectives of each major theme.
- A designer compiled all this information onto a visual platform.

M: Regional Scale Cultural Maps

Māori have been spatially articulating their relationship with all the islands that form Aotearoa NZ ever since they arrived (Hakopa, 2019). However, European colonization through its many violent manifestations has led to significant erasure of both place-based and more mobile renditions of Māori landscapes (Pawson and Brooking, 2013). The maps being produced by the

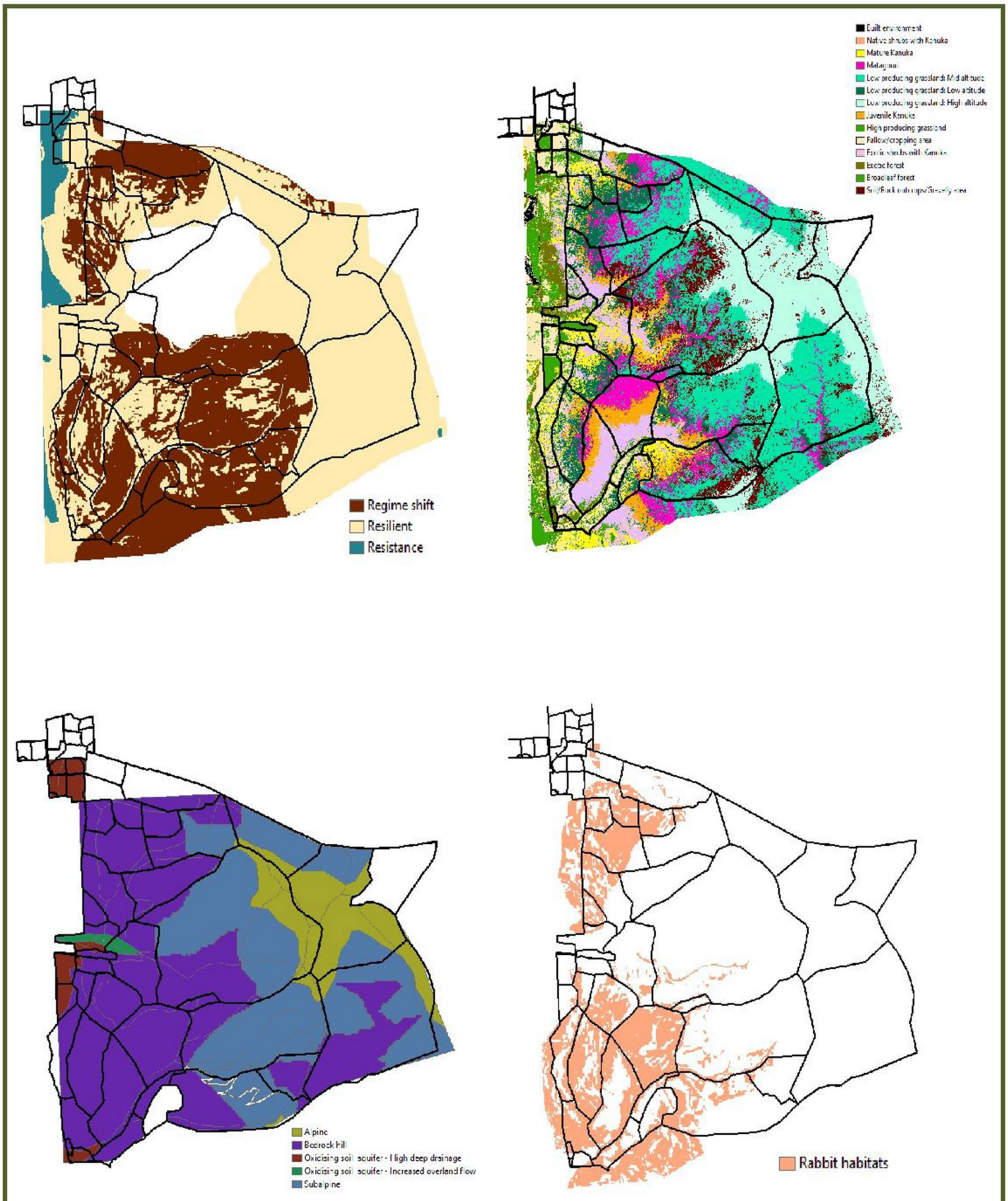


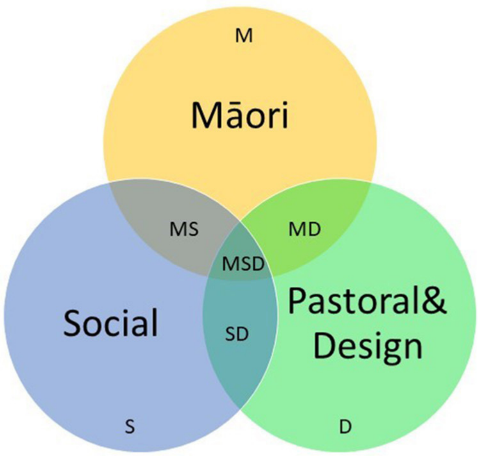
FIGURE 8 | Farm scale mapping of key pastoral and landscape health variables.

Māori team at the COE attempt to challenge this cartographic reality, but to also provide a more holistic visualization of human-land relationships which contain material (lakes, trees, houses) as well as non-material elements (stories, spirits, emotions).

An example of a map made by the team is given in **Figure 11**.

This map spatializes the cultural history of the landscapes within which Mt. Grand is situated and is intentionally on a regional scale to include the vital stories of how the landscape features we see in that region came to be.

Rākaihautu's story of digging the lakes of the South Island with his magical *ko* (digging stick) and filling them with food, including lake Wānaka which is next to Mt. Grand, is presented in this rendition. Along with that are stories about Aoraki



Name	Knowledge Products
M	Cultural Maps
S	Relational community wellbeing report
D	Farm scale future master plan
MD	Regional scale SES mapping
SD	Design Critique Assessments
MS	One Land Many Stories visualization

FIGURE 9 | Knowledge co-production at the COE across different teams.

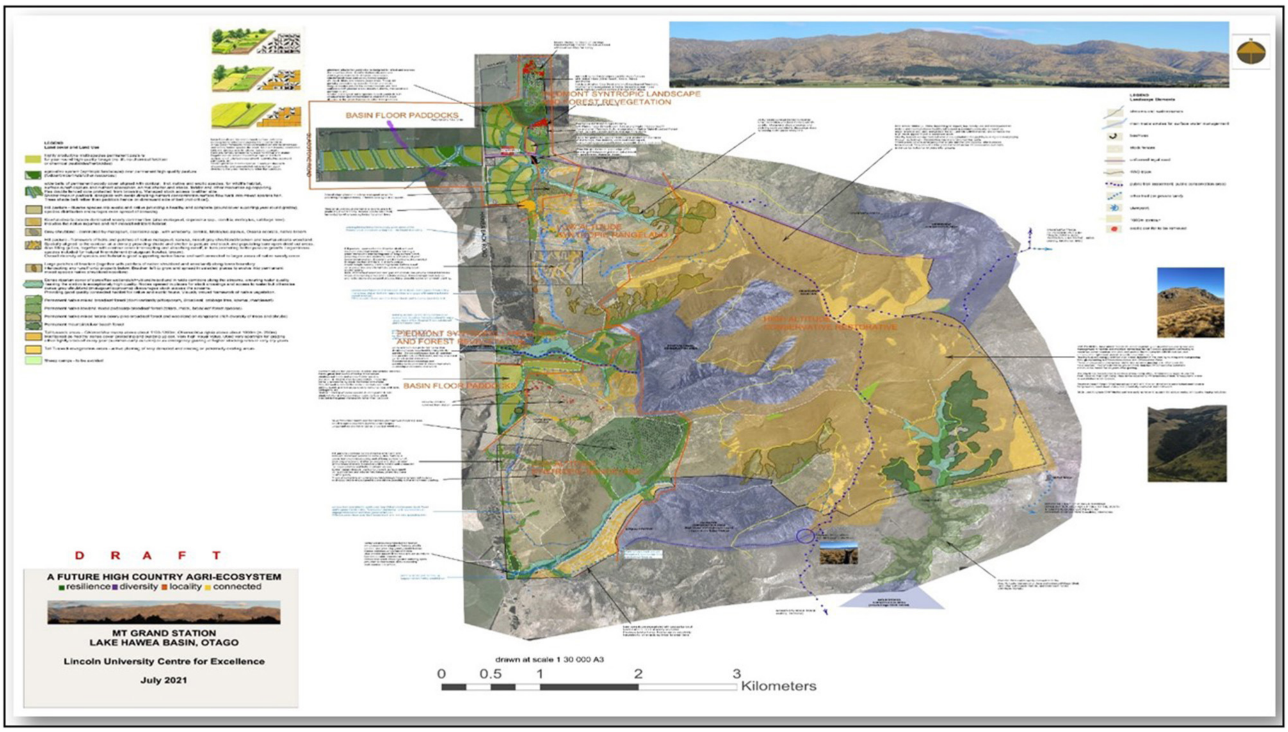


FIGURE 10 | Mt. Grand re-design plan.

(Aotearoa NZ's highest mountain) and his brothers as well as the cultural history of the Mata-Au River. Finally, as *katiaki* of the regional district state,

"Our associations are much broader than discrete sites. An archaeological site will contain items, but we are talking about is the *korero* (conversation and dialogue) which goes with a place and that blankets a place like a *korowai* (cloak), overlays it, which does not have very strong boundaries"

The goal with this map is to move the COE's focus out of the farm-scale and current and future thinking, into the regional cultural landscape and the past. Additionally, it is to present a landscape version that questions the different "boundaries" that are used in current landscape planning to characterize things like urban zoning, conservation habitats, sustainable food gathering sites, watersheds, and primary production zones. Finally, it also complements and supplements current notions of relationships

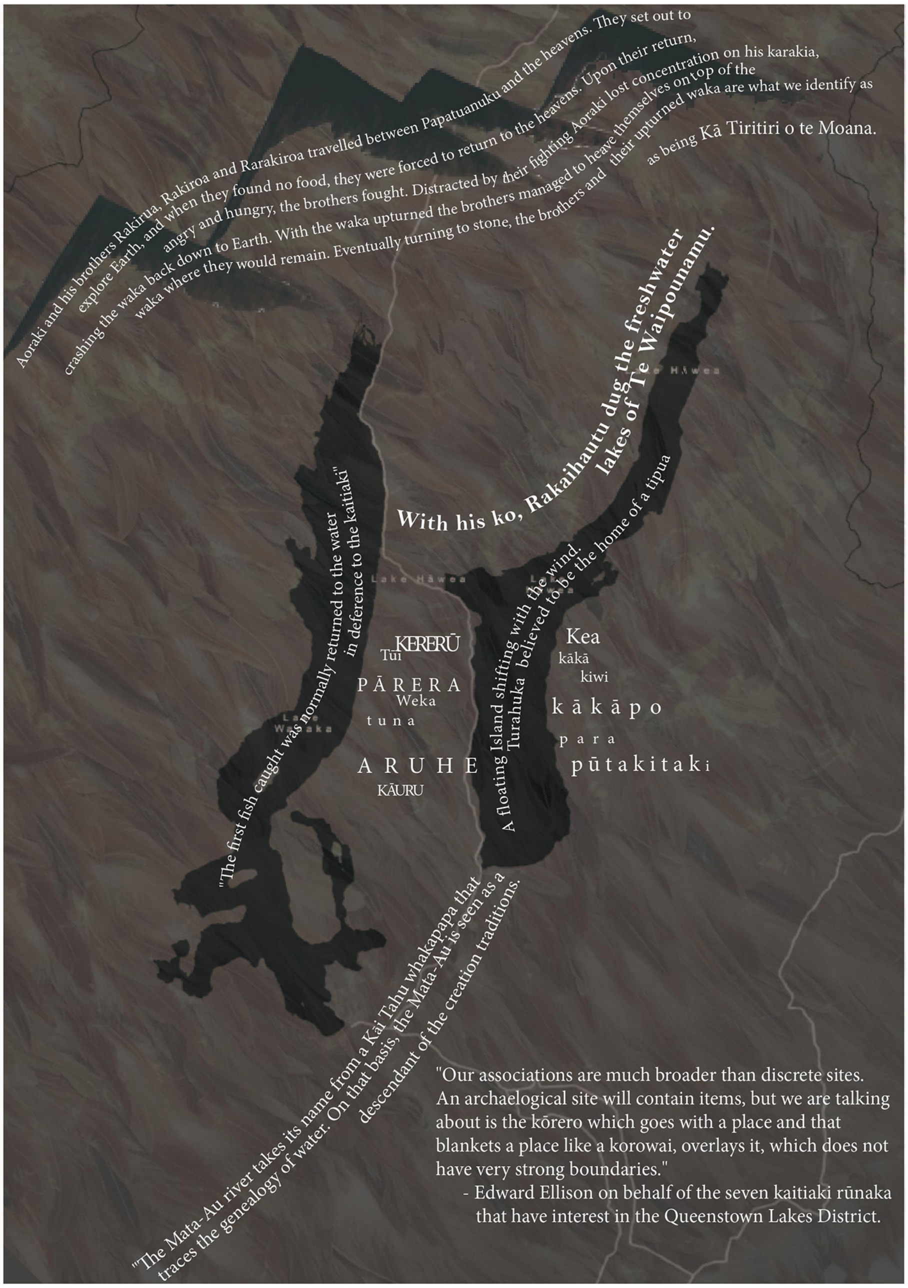


FIGURE 11 | A cultural map of the Mt. Grand region.

between various landscape forms such as rivers, mountains, farms, and cities.

The tools highlighted in this effort are indigenous cartography, visual storytelling, emotional and affective landscapes, and participatory mapping. In detail, the process entailed,

- Engaging with The Ngāi Tahu Cultural Mapping Project (https://www.kahurumanu.co.nz/) to get permission to use their cultural maps.
- Identifying vital points/processes of importance from various maps prepared by *iwi*, councils, and *Papatipu Runangas*. These maps also go back in time to highlight some of the historical changes in ownership and management.
- Co-design meetings about which stories to use, their significance for the landscape, and their role in exploring social-ecological well-being for the future.
- A Māori designer looked over the identified stories, existing landscape forms, and statements from the regional *iwi*, councils, and *Papatipu Runangas* and created the map.

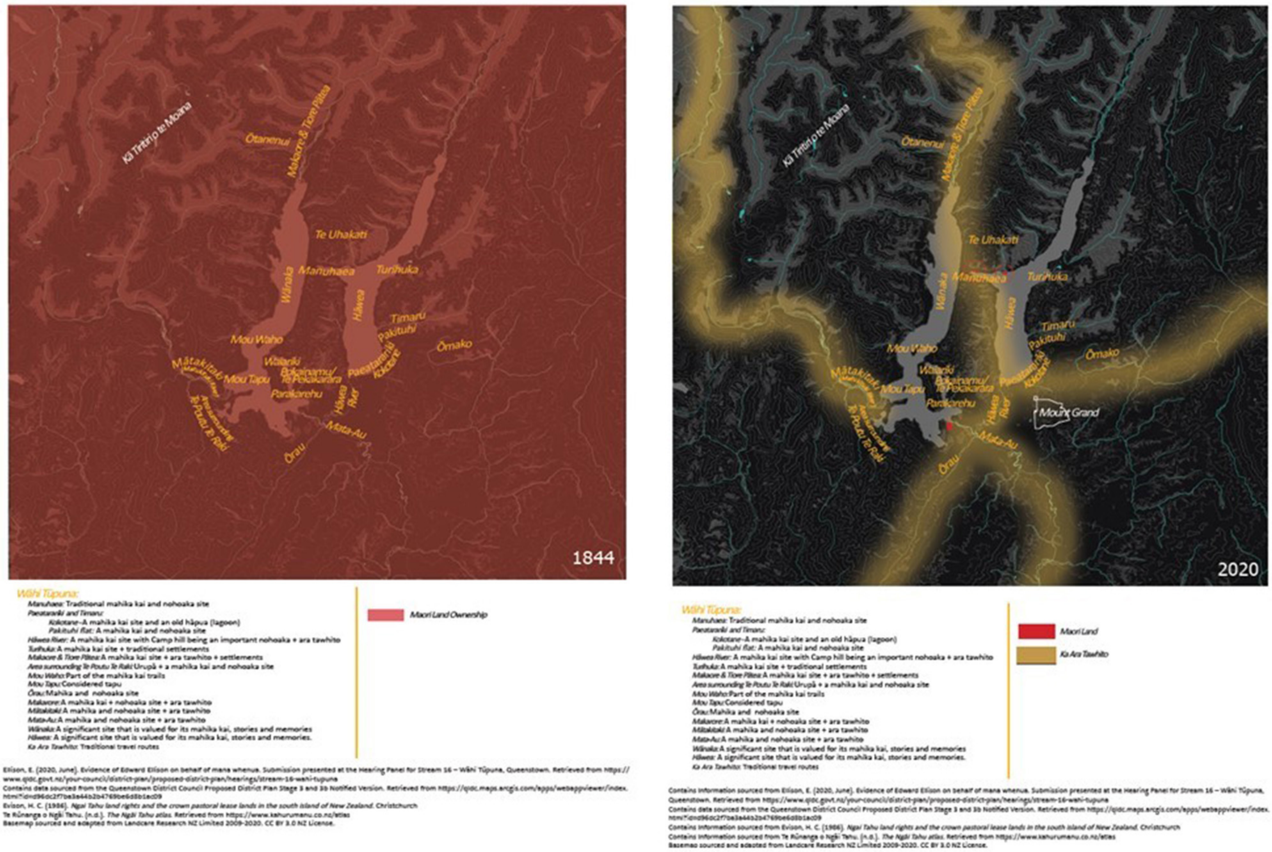


FIGURE 12 | Co-produced maps showing the transformation in land ownership in the Otago region of Te Waipounamu South Island in Aotearoa NZ. Also depicted on the map are *Wahi Tupuna* (sacred/ancestral places) which include *Mahinga Kai* (food gathering site) and *Ka Ara Tawhito* (seasonal migration routes).

MD: Regional Scale SES Mapping

Co-production of maps that attempt engagement across the constituent and Māori knowledge systems has been a very contentious and productive undertaking at the COE. During the co-design phase, there were significant challenges between the Māori team and the landscape design team, especially regarding the spatialization (and visualization) of immaterial objects, beings, and processes and the scalar biases of attempting landscape design from the perspective of existing land ownership and zoning laws. Despite significant divergences in the values, objectives, and goals of the project, the Māori and design team managed to collaborate on producing a few visualizations which attempt to include plural goals and tools.

A couple of examples are shown in **Figure 12**. The two maps were produced in collaboration with a Māori designer and a spatial analyst using data from historical narratives of Māori movement across the landscape and over time change in ownership of land in the south island from the Whenua Māori Visualization Tool developed by Te Puni Kokiri Ministry of Māori Development and Manaaki Whenua Landcare Research (https://whenuaviz.landcareresearch.co.nz/).

The *Ka Ara Tawhito* (seasonal migration routes highlighted in yellow) shown in (**Figure 12**) crisscross a vast landscape from the mountains to the ocean and reveal the vast and dynamic territorial presence of the Māori. In doing so they challenge colonial notions of land use rooted that remain overwhelmingly rooted in more sedentary notions of communal infrastructure. Simultaneously they visualize, throughout more than 170 years, the changing control over the land, from Māori to the settler colony.

Visualizing these *Wahi tupunas* allows a different landscape to emerge and facilitates the process of cultural and political inclusion and ultimately, plurality. Concepts such as deed validated land ownership, productivist management, and intensive livestocking are challenged in this visualization. Additionally, due to protocols and procedures enshrined in the Treaty of Waitangi (Ataria et al., 2018), such revelations necessitate all landscape management programs to be co-developed in consultation with Māori stakeholders. Therefore, even though the current MT. Grand management plans fail to account for the significance of the migration routes, our visualization makes the case that it should. Additionally, they can also be used as "boundaries" for demarcating land, paralleling existing land demarcations that remain rooted in the notion of property ownership and sustainability equilibriums between production and conservation.

DISCUSSION

In their review of co-production practice, Jagannathan et al. (2020) note that co-production practice is often hindered and fails to address the objectives of co-production theory due to existing power differences and the bounding of co-production projects by institutional and funding realities. The work done at the COE echoes this insight, especially when viewed from the perspective of more radical, long-term transformations in social-ecological relationships. Keeping this in mind, we return to the questions we began with and explore the major synergies and challenges that emerged during knowledge co-production. We argue that the COE's experiments with co-production reveal four important points.

First, designing, managing, and sustaining co-production should be pursued with a significant focus on the co-definition of values and objectives and require mitigation procedures in place to explore how different values can coexist within the co-design space. Our initial forays toward co-design were quite contentious with significant challenges when it came to defining how knowledge should be produced, who should it serve, and what the group should aspire for. The COE did not have the resources in place to mitigate these cleavages, and many contentious exchanges, especially those that were problematic from a Māori perspective were tabled at an impasse. This was especially problematic for the indigenous stakeholders who were burdened with not just continuously exposing their historical trauma but were also kept from forging truly innovative concepts in collaboration with the more mainstream views of sustainability. This is reflected in significant challenges that were recorded between the Māori and Design teams, but also in the fact that in stage 1 of Co-design the COE team as a whole did not spend enough time discussing the more essential "values" underpinning our work or exploring tools and techniques for "engagement" across the different disciplinary and ideological silos. Instead, as has been recorded in other co-production attempts, much of the conversation, even in the initial stages was around the appropriate methodology (Parsons et al., 2016; Sutherland et al., 2017; Turnhout et al., 2020).

Second, it is important to understand that co-production with multiple stakeholders should be aware of what that represents for different groups given both their current capacities and historical inclusion (or exclusion) within the process of knowledge production. Therefore, one of the moments of synergy in the COE was the acceptance that IPLC stakeholders had been part of multiple projects in the past and were also currently burdened by invitations from other such initiatives. This led the COE team to decide that the inclusion of multiple stakeholders would have to be contextual, especially when the institutional timeframes for the university and those of IPLC actors were very different. So, while the COE team embraced, what can be termed, "weak" co-production, limiting the inclusion of IPLC to a few key actors during the co-design phase, they were responding to IPLC stakeholders who expressed that they wanted a more "concrete" idea of what the COE was proposing before investing their time and energy. We believe, pursuing such active representation, can address the problem with tokenism which co-production has struggled with (Reid and Rout, 2018; Zurba et al., 2021).

Third, COE remains more focussed on methods that lead to tangible knowledge products and less on evaluating such products for the realization of plurality, accountability, and engagement. As mentioned in **Figure 2** the salient features driving our work at the COE foreground these elements. However, finding synergistic evaluation tools for the work done by various teams has been quite problematic, especially since the assessment of the products must be inclusive. While scholars do mention certain pathways for addressing the evaluation problem, converting theory to practice has been marred by challenges to the viability of different metrics (Polk, 2015; Norström et al., 2020). For example, assessing the co-produced regional scale map led to questions about whether Māori stakeholders wanted a plurality of concepts and aspirations to define their visualization of the land, or whether they wanted their goals of sovereignty to be the final value being measured. This also raises a point made by Wyborn et al. (2019) that co-production does not always lead to "better outcomes." However, in the case of the COE, due to the lack of assessment tools, we find it hard to agree or disagree with this proposition.

Finally, both synergies and challenges proved to be equally meaningful when pursuing co-production. The discussions that took place during the co-design meetings were incredibly useful in presenting very clearly the disciplinary silos and the different understandings of knowledge production that existed on campus. As many scholars have pointed out that there is a greater need to engage with the politics of knowledge production, and the discussion meetings, the participatory design theme setting, and the process of map-making brought this to the forefront. While the team at COE is still working on finding places of engagement across the different intra-group teams that were formed, there is a clarity in the objectives and values of different actors which did not exist at the beginning of the process.

We think the work done at the COE echoes two ongoing, unresolved problems in knowledge co-production.

First is the mismatch between more radical and socio-ecologically transformative ideological goals and the more pragmatic, functionally useful outcomes from the practice (Tengö et al., 2017; Jagannathan et al., 2020). We think this cleavage is sustained by the very different funding and institutional realities of academic, project-oriented knowledge production and the complicated, historical problems that require long-term, multi-spatial solutions. A great example is the differences between the farm-scale maps and the regional cultural maps. The farm-scale maps address the needs of a land focussed institution of higher learning that the COE is based on to provide innovative land management ideas which also respond to the insecurities of regional farmers. However, the cultural maps being produced by the COE address the latent issues of power within a settler-colonial society and how they manifest onto the land across a long period. Therefore, currently, the landscape is divided into multiple parcels, each of which depending on their ownership and use, are held accountable to different sets of ecological and social compliance, but this system of relating to the land deviates considerably from pre-colonial Māori visions of stewardship and ownership. Lacking this time dimension, managing land ends up constrained by the myopic vision of a certain administrative reality and it can be argued, a very specific human/nature relationship. The maps highlight a process of place-making that challenges current visions of ownership, control, and democracy, which remain tied to specific visions of personal property and renditions of history that fail to capture Māori land use. The land dispossession caused by colonial capture of Aotearoa NZ is an unresolved issue, whose ongoing impacts are well-documented (McIntyre, 2007; Forster, 2016; Ojong, 2020). Thus, while our work through cultural mapping attempts to reveal the limitations of juridically ordained indigenous land rights in facilitating land and agro-pastoral management that is healthy and equitable, responding to a longer more transformative goal, our farm-scale map addresses the needs of the university to experiment with innovation which also respects the anxieties of regional farmers.

Second, building off the earlier point there is a lack of multi-scalar and multi-temporal knowledge production for multi-functional landscapes (Stürck and Verburg, 2017). While there is a bewildering diversity of knowledge available to land managers and policymakers (Maharjan et al., 2019; Paltsyn et al., 2019; Chaudhary et al., 2020). Presenting such knowledge in formats that appeal to a variety of stakeholders is critical to ensure both the sophistication and the democratic potential of land management. Additionally, the tools of exploration (satellites, field workers, farm system outputs), due to their scalar biases, are talking past each other rather than with each other. Ultimately, contingencies of capital, manpower, and time often limit research programs and policymakers to extrapolate their findings onto the relevant land unit. Our work addresses such issues by (1) holding different scales (farm, person, region, etc.) as non-constitutive, that is, the seemingly larger units are more than the sum of the smaller ones (2) by attempting to work on projects across as many unique scalar units as possible (3) By including time as a key component of scale, especially when co-producing knowledge with indigenous stakeholders.

Ultimately, the experiments with co-production at the COE while seemingly time-consuming (30 months) have begun to delve into the critical aspects of engagement—ensuring the disciplinary marriage we have been searching for, and inclusion—which given our current more tangible objectives would incentivize IPLC to come to the discussion table. And, this is when we need to focus on sustaining the co-production through building on the non-exploitative and non-extractive relationships that we have worked hard to establish between the various stakeholders.

CONCLUSIONS AND THE WAY AHEAD

At the COE, with the goal of re-designing a farm to function as a multi-functional landscape, we attempted a process of knowledge co-production to ensure equitable representation of different stakeholders in a certain region of Aotearoa NZ. This process was documented through ethnographic participatory observations of meetings and workshops and materialized through knowledge products that emerged from this collaboration. We did thematic and qualitative coding of these exchanges and explored whether the actual process of knowledge production addressed the salient features guiding the work. While our work led to some vital insights into co-production, especially in regards to co-designing for plurality and inclusion, which led to land visualizations at different scales and temporalities, significant work remains to be done to address both IPLC inclusion throughout the process and to create assessment frameworks that can adequately evaluate such co-production. We draw the following three lessons from our work.

First, the COE, and similar initiatives at knowledge co-production, while pursuing stakeholder inclusion need to facilitate more opportunities for various segments of the IPLC population to engage with the project. While in the past the COE was advised by representative stakeholders to hold off on such contact before constructing a more concrete set of objectives and some tangible examples, we are currently ready to collaborate and need to pursue this in the future.

Second, while the COE has been successful in creating some collaborative knowledge products, we have important shortcomings when it comes to evaluation metrics. Our future work needs to focus on experimenting with different assessment frameworks and we have already started engaging with existing options. This is especially important given the diversity of indicators and variables in multi-stakeholder, multi-functional landscapes, and is a significant data gap

Third, the mismatch between both scales of knowledge production as well as its ideological goals can be a significant roadblock to achieving successful co-production. Such mismatches can be addressed through long-term trust-building with IPLC communities, conducting multiple projects exploring similar objectives at different scales, and finally, pursuing research that has utility for IPLC aspirations that go beyond mere knowledge production.

We conclude with a call for more studies that assess the process of knowledge co-production especially with IPLC focussing on highly contentious topics such as land management and re-design, which foreground issues that stem from disciplinary bias, colonial erasure, and the marginalization of non-expert opinions. While it can be a very difficult task addressing questions of values, objectives, and inclusion, especially when there are glaring power inequalities across stakeholders, it can foster a culture of constantly reflecting on whether power is shared and how the practice of co-production needs to be actively gauged against the aspirations of co-production. As institutions and governments around the world mobilize to address the various crises stemming from land use, climate change, and unequal resource distribution, the care of landscapes has become a critical issue. Planning this care requires a direct engagement with the historical relationships between the various stakeholders and understanding how that manifests into producing knowledge to sustain such plans. Exploring this knowledge production and evaluating its viability through a prism of diversity and utility will be essential in ensuring its success and can create truly inclusive multifunctional landscapes. We suggest that knowledge co-production attempts in multi-stakeholder landscape design and management should attempt similar assessments of their process to ensure the relevance of the research to the various stakeholders.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Lincoln University Human Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

RC did all the writing, human subject field work, and analysis of the knowledge co-production data. SJ produced the farm scale maps. HM and LM produced the Maori cultural maps. JE, SD, and PG provided editorial support. All authors contributed to the article and approved the submitted version.

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One Place Doesn't Fit All: Improving the Effectiveness of Sustainability Standards by Accounting for Place

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The growing interest in incentivizing sustainable agricultural practices is supported by a large network of voluntary production standards, which aim to offer farmers and ranchers increased value for their product in support of reduced environmental impact. To be effective with producers and consumers alike, these standards must be both credible and broadly recognizable, and thus are typically highly generalizable. However, the environmental impact of agriculture is strongly place-based and varies considerably due to complex biophysical, socio-cultural, and management-based factors, even within a given sector in a particular region. We suggest that this contradiction between the placeless generality of standards and the placed-ness of agriculture renders many sustainability standards ineffective. In this policy and practice review, we examine this contradiction through the lens of beef production, with a focus on an ongoing regional food purchasing effort in Denver, Colorado, USA. We review the idea of place in the context of agricultural sustainability, drawing on life cycle analysis and diverse literature to find that recognition of place-specific circumstances is essential to understanding environmental impact and improving outcomes. We then examine the case of the Good Food Purchasing Program (GFPP), a broad set of food-purchasing standards currently being implemented for institutional purchasing in Denver. The GFPP was created through a lengthy stakeholder-inclusive process for use in Los Angeles, California, USA, and has since been applied to many cities across the country. The difference between Los Angeles' process and that of applying the result of Los Angeles' process to Denver is instructive, and emblematic of the flaws of generalizable sustainability standards themselves. We then describe the essential elements of a place-based approach to agricultural sustainability standards, pointing toward a democratic, process-based, and outcome-oriented strategy that results in standards that enable rather than hinder the creativity of both producers and consumers. Though prescription is anathema to our approach, we close by offering a starting point for the development of standards for beef production in Colorado that respect the work of people in place.

Keywords: food system, agricultural sustainability, food policy, urban-rural linkages, local food

INTRODUCTION

The environmental sustainability of agriculture has become a subject of major interest, with many calling for a wholesale restructuring of agricultural systems within a social-ecological framework that ensures adequate provisioning of food while also protecting (or improving) the environment (Pretty, 2008; Gordon et al., 2017). These calls are a reflection of agriculture's large environmental impacts; agriculture occupies about 38% of earth's land surface, causing roughly 70% of projected biodiversity loss and anywhere from 10 to 45% of anthropogenic greenhouse gas emissions (Foley et al., 2011; Garibaldi et al., 2017). These impacts are projected to increase as production levels rise and purchasing habits change among the projected population of 10 billion by 2060 (Pelletier and Tyedmers, 2010; Gerland et al., 2014; Hunter et al., 2017).

In addition to scientific research to help identify best practices, the transition to a more environmentally sustainable agriculture can be supported by making adoption of those practices economically advantageous to producers (Blackman and Rivera, 2011). Such governance has historically been the domain of international and national regulation, wherein best practices were enforced by fines and other punitive measures (Brunsson and Jacobsson, 2000). Increasingly, though, adoption of sustainable agricultural practices is supported through voluntary production standards which, instead of the "stick" of punitive measures, offer the "carrot" of increased product value (Ponte and Cheyns, 2013; Tayleur et al., 2017; Lambin and Thorlakson, 2018). As environmental attributes are often invisible to the consumer, this increased value relies on the development of broad "sustainability networks" to create, verify, and enforce standards, thereby establishing recognizability and credibility with consumers (Ponte and Cheyns, 2013; Bonroy and Constantatos, 2015).

However, agriculture is fundamentally place-based, with culture, climate, history, and other local circumstances interacting in complex ways to create production systems with distinct environmental impact profiles. For example, life cycle analysis estimated the normalized water footprint among six fundamentally different beef production systems in New South Wales, Australia as ranging from 3.3 to 221 L of H_2O equivalent per kg of live weight (Ridoutt et al., 2012). Though it is just one component of environmental impact, that the water footprint of beef production can vary by a factor of 67 within a single Australian state points to the complexity inherent to broad-scale agricultural sustainability assessments, and more specifically to the simplification behind all-too-common generalizations about beef production.

The apparent contradiction between the placed-ness of agriculture and the placeless-ness of generalizable agricultural sustainability standards is the subject of this policy and practice review. Specifically, how can broadly applicable sustainability standards improve environmental outcomes if those outcomes are dependent on highly place-based factors? Is it possible to design sustainability standards that are widely recognized and trusted while also locally adaptable? We examine these questions by drawing on lessons from our work on an initiative in Denver, Colorado, USA, aimed at increasing the share of Colorado-grown agricultural products in City of Denver institutions. This still-evolving initiative is guided by the Good Food Purchasing Program (GFPP), a food system rating metric that integrates a set of well-known, third-party sustainability, food justice, economic, and labor standards (Lo and Delwiche, 2016). Though we have worked with producers from many agricultural sectors, we focus on beef production for most of our examples because it is a significant component of Colorado agriculture and among the most controversial sectors.

We begin by reviewing the idea of place, including sociological, political, and ecological conceptions. We do so in the context of agricultural sustainability, integrating lessons from life cycle analysis and literature from multiple disciplines. How important to a proper understanding of sustainable agriculture is knowledge of place-specific circumstances? Next, we discuss place in the context of agricultural sustainability standards. We review the literature on the role of such standards, with an eye toward the political dimensions of their design and implementation. Do top-down, generalizable standards preserve the *status quo* and prevent a broad re-envisioning and restructuring of the food system? Are there tradeoffs involved in implementing a more democratic approach? To explore these questions, we take an in-depth look at the GFPP. Finally, we propose a starting point for creating place-adapted sustainability standards for Colorado, again using the example of beef production.

PLACE AND LIVESTOCK

How might we situate "place" in studying the deployment of beef sustainability standards? Though often implicitly and sometimes explicitly used to shape the way we think about standards, "place" can mean a variety of things. Does it refer to the innumerable, unique combinations of landscape features such as soil texture, hydrology, weather patterns, terrain, and biota? Is it determined by government boundaries, property ownership, and/or production and consumption? Or perhaps it may refer to a sense of home or belonging, or remind one of where they feel "at home"? All of these impulses signify boundaries and flows, whether they be social, political, economic, or biophysical. Indeed, the meaning, function, and construction of place can be viewed through many lenses. In the end, practice helps us understand how place is constituted by this variety of forces. In the social sciences, practice theory grounds phenomena like knowledge, values, feelings, emotions, and affectivities in everyday encounters and activities, emphasizing endogenous and emergent dynamics (Carolan, 2017). It argues that practices are the ongoing flow, or habituation, of these dynamics as manifested at a given point in time.

A biophysical approach to place often centers upon bioregionalism. This includes, for example, particular natural communities or watersheds, as well as unique human cultures which arise out of the natural limits and potentials of a region (Lynch et al., 2012). Bioregional beef production is generally adapted to local precipitation, soils, climate, and biota. For example, precipitation generally decreases from east to west across North America. In addition to influencing the types and quantity of plant biomass, this precipitation gradient, combined with other biophysical differences, would be expected to strongly influence the suite of appropriate management practices for beef production. For instance, a beef producer in New York, USA can graze the same pasture several times in one growing season without degrading it, while those in Colorado, USA generally graze unirrigated pastures just once. This fact alone has significant impact on recommended stocking rates to support regenerative land management recommendations.

As a second example, in the southern latitudes of North America with subtropical climates, *Bos indicus* breeds, which are evolutionarily adapted to high heat and humidity due to greater skin surface area enabling greater heat evaporation, are common. These breeds can effectively produce beef and milk for human consumption despite the environmental stress of the local climate. In more northern latitudes, *Bos taurus* breeds, such as Angus cattle, are more common. Their thicker hair coat and greater fat storage capacity make them better suited to colder climates than their *Bos indicus* counterparts. The thicker hair coat and dark coloring of black Angus cattle make them less well-adapted to sunny, hot, and humid climates. However, these cattle are also common at southern latitudes despite their lack of evolutionary adaptation. While individual animals can adapt somewhat to novel environments, this ability to adapt does not make them better suited to hot and humid climate conditions than *Bos indicus* cattle and therefore does not alone explain the prevalence of these breeds at southern latitudes.

Clearly, then, management practices are based on a constitution of place that is more than simply biophysical or bioregional. The practices of a beef producer in eastern Colorado, USA share much more in common with a beef producer in Virginia, USA than they do with pastoralists in the grasslands of Mongolia, who face more similar biophysical challenges. As an example of how environmental outcomes are disproportionately affected by the dynamics of place, we point to the broad range of environmental footprints for beef production systems across the United States. Recently, the U.S. beef industry commissioned the most comprehensive, national assessment of beef's environmental footprints (Rotz et al., 2019). To accomplish this task, beef producers from every state except Alaska were surveyed and/or interviewed about their management practices (Asem-Hiablie et al., 2015, 2016, 2017, 2018a,b). "Representative operations" were developed from the information reported by producers and were analyzed for their production and environmental footprints following a methodology developed by Rotz et al. (2013). All environmental impacts incurred on the farm and in the production of farm inputs were considered in this analysis ("cradle-to-farm gate"). The study evaluated beef production systems for their carbon footprint (a measure of greenhouse gas emissions per pound of beef produced), reactive nitrogen footprint (a measure of reactive nitrogen loss per pound of beef produced), water footprint (a measure of non-precipitation water use per pound of beef produced), and fossil energy footprint (a measure of non-renewable energy use per pound of beef produced).

Two pertinent conclusions are drawn from the results of this study, further justifying the need for place-based sustainability standards. While environmental impacts are a function of both management practices and biophysical processes, biophysical place was a greater driver of the differences in environmental footprints between regions than management practices despite the fact that some practices are clearly manifestations of socioeconomic conceptualizations of place (Rotz et al., 2019). As an example of biophysical conceptualizations of place driving environmental outcomes, reactive nitrogen losses are driven by climate and soil type. As a result, reactive nitrogen footprints were greater in wet than arid regions, irrespective of differences in management practices across regions. This was partially correlated with differences in management practices, with operations in wetter regions also using more nitrogen fertilizer than operations in drier regions.

On the contrary, as an example of socioeconomic conceptualizations of place driving environmental outcomes, the arid and semi-arid climates of the states in the Southwest, Northwest, Northern Plains, and Southern Plains as defined in the study might lead one to conclude that crop production was minimal in these regions. However, the technological advancement of irrigation enabled crop production in these regions, and thus resulting in greater blue water (i.e., surface and ground water) footprints than wetter regions. Were biophysical constraints the sole arbiter of practice, crop production would be less common in these regions. As demonstrated, generalized sustainability standards inherently cannot account for differences in bioregional place, thus reducing their efficacy in achieving their objective of mitigating environmental impacts.

Interestingly, the authors concluded that recommendations to improve the sustainability of beef cattle operations across the U.S. should not be made using national generalizations; rather, they should be made on an individual operation basis. Clearly, sustainability standards which enforce generalized practices may result in more harm than good, due to the interaction of biophysical processes with management.

If we extend our understanding of place to include political, economic, and socio-cultural elements, we see that it is problematic to expect people in a locale to have the agency to achieve sustainability, especially as defined by others not of that place. For example, the Green Revolution has been repeatedly criticized for its promotion of a one-size-fits-all approach to food security, which is to say, it is based heavily on standardized (i.e., place*less*) knowledge and practices (Carolan, 2018). A core principle, then, to emerge out of movements looking to supplant this mindset is to afford *situated* supply chains, which refers to food and production systems that are informed by a place's ecological, climatological, socio-cultural, infrastructural, and economic realities (Perfecto et al., 2009). Standards aimed at enhancing principles such as environmental sustainability or community resilience, especially those exported from elsewhere, can therefore present a challenge when not properly grounded to those situated nuances.

The way that standards are exported from elsewhere is also a reflection of how place is tied to various scales of government and economics, of which there can be contention and power imbalances concerning who or what does or ought to constitute place. For example, some have found that the meaning people ascribe to place is connected to ideas about property, conservation, and governance, of which there can be disagreement (Yung et al., 2003). This suggests that decision-making and forms of government are actively constructing and maintaining "place." Others emphasize the roles of markets in relation to place. For example, some examine the potentially valuable role of scaling-up localized agricultural markets (e.g., Friedmann, 2007), while others have problematized what "local" means in this context (e.g., Hinrichs, 2003). Economic approaches may also be focused more on the role of global markets on the development of particular places (Raynolds et al., 2004). However, others have argued that global market forces must be challenged through various forms of citizenry which marries alternative markets with environmentalism through common ties to place and physical engagement with place (DeLind, 2000; Reid and Rout, 2016).

Socio-cultural perspectives are often more focused upon the social construction of place. For example, some have defined place "as a space that has been imbued with meaning through personal, group, and cultural processes" (Cross, 2015, p. 494), where, biophysical, political, and economic processes and boundaries are subsumed by socio-cultural meaning of a space. From a more critical perspective, others focus upon how place often shapes and is shaped by community ideology (Hummon, 1990). Put another way, place is constructed through the articulation of a sense of belonging, which is based upon various ties of sentiment, interest, value, and knowledge. Further, place is a historical process based upon social practices related to inequality, difference, power, politics, interaction, community, and social movements (Gieryn, 2000).

We argue that social, political, economic, and biophysical processes are all valuable in conceptualizing place. To tie these together, we suggest understanding place as the result of practice. Place as a practice refers not only to what people do within place-based biophysical constraints, but also recognizes how place is constructed by social, economic, and political practices, which may transcend biophysical boundaries. This approach to place emphasizes it as a process that shapes, and is shaped by, people in both material and symbolic terms. As Camus observed, place is "not just something people know and feel, it is something they do" (Camus, 1959, p. 88). Put simply, practice is what is done to connect how people feel about place with what they know about place and may not necessarily be tied to experience in a locale, but often is. Taken historically, this suggests that place can be a moving target, and one in which culture and politics tend to shape how place gets done as much as climate or biota.

If a more holistic conception of place is essential to understanding both management practices and outcomes in beef production, and if this is bound to be spatiotemporally dynamic and multivariate, this has important ramifications for creating and applying standards to advance agricultural sustainability. Indeed, given not only the reality but the importance of the dynamism of place, it may be that generalized, static, or externally imposed standards may not be merely ineffective but potentially harmful. However, as we have seen, sustainability standards must be broadly recognized to be credible and therefore effective. Building the foundation for reconciling the apparent contradiction between the importance of place in agriculture and the effectiveness of sustainability standards is the subject of the rest of this paper.

PLACE, PRACTICE, AND SUSTAINABILITY STANDARDS

Standards are a ubiquitous aspect of modern life. They are the indicators and measures by which people, practices, processes, and products are assessed (Loconto and Busch, 2010). However, the metrics used for evaluation, such as sustainability measures, can have unintended consequences (Rosin et al., 2017). Indicators can also be viewed as fallible, especially in the context of sustainability assessments (Bell and Morse, 2008). However, others have suggested the utility in viewing indicators of sustainability as performative—as building toward particular worlds (Hale et al., 2019). This approach views standards from a more pragmatic perspective that acknowledges their limitations but posits the impact that they can have on iteratively generating conversations and relationships that may have not have otherwise occurred.

Yet, standards themselves can constrain sustainability practices and conversations. For one, broadly applicable standards are necessarily constrained to assessing broadly used production practices. This may limit qualifying producers to those within the mainstream, and thereby play a role in preserving rather than challenging the *status quo*. Indeed, the outcomes of forms of accountability, such as standards, are related to how effective the participatory processes were in shaping the standards, suggesting a tension between socializing forms of accountability and standards which can de-socialize practices (Hale et al., 2020). In other words, democratic and participatory processes are vital to constructing just, place-based standards.

The Good Food Purchasing Program

Like many cities, Denver, Colorado, USA is exploring how its institutional food purchasing policies can be adapted to better support its broader, values-based goals (Jablonski et al., 2019). These values relate to environmental sustainability, food and economic justice, and regional purchasing to better support local communities and economies, including regional rural communities. Toward this end, the Denver Sustainable Food Policy Council (SFPC), one of the city's Mayor-appointed Boards and Commissions, created a City Food Purchasing Standard Policy Working Group. Through this working group, the SFPC has recommended the implementation of the Good Food Purchasing Program to "stimulate a robust and resilient world class food system through sound institutional purchasing policies" (Denver Sustainable Food Policy Council, 2018, p. 1).

The GFPP emerged from the work of the Los Angeles Food Policy Council (California, USA). Recognizing that institutions across the U.S. spend billions of dollars on food purchases, and that these purchases can be reapportioned via policy change to better achieve non-financial goals, Los Angeles set out to create and apply a rigorous and systematic process for incorporating values into its food procurement process. Creating the GFPP in Los Angeles was the culmination of a two-year, multi-stakeholder process that included "the Food Chain Workers Alliance, Natural Resources Defense Council, Compassion Over Killing, and the Los Angeles County Department of Public Health, as well as farmers, processors, distributors, chefs, large public and private institutional buyers, school food advocates, and faith-based leaders" (Lo and Delwiche, 2016, p. 187). While all stakeholders recognized the importance of leveraging the buying power of large institutions to create food system change, the leaders of this effort note that the process of creating standards to meet a multitude of goals was often conflicted (Delwiche and Lo, 2013; Lo and Delwiche, 2016). Nevertheless, the diversity of the group and the length of the process were noted as strengths.

Ultimately, the GFPP was structured to address five "values": local economies; environmental sustainability; valued workforce; animal welfare; and health and nutrition. It consists of a tiered, points-based rating system whereby participating institutions can choose how aggressively they want to pursue improvement in each of the value categories. However, the GFPP does require that institutions meet baseline standards in each category, so that "institutions are not able to limit themselves to changes that are easy" (Lo and Delwiche, 2016, p. 188). Though implementation is ongoing in Los Angeles, the program notes that, through implementation by the city school district, $12 million has been redirected to local produce purchasing, "healthier" breads have been made available, 150 jobs have been created, antibiotic free chicken is now being purchased, and a 15% decrease in meat spending has been realized with the addition of "meatless Mondays" (Bronsing-Lazalde, 2020).

A key innovation of GFPP is the use of existing, well-known third-party certification programs. For example, the environmental sustainability value includes such standards as American Grassfed Association, Animal Welfare Approved, Food Alliance Certified, Seafood Watch, and U.S. Department of Agriculture Organic. Qualification for different standards achieves different "levels" under each of the value categories. Use of broad-scale standards makes the program relatively easy to implement in other municipalities, as opposed to following Los Angeles' extensive process in each place. Many cities across the US are in various stages of implementing GFPP, including: Austin, Texas; Chicago, Illinois; Cincinnati, Ohio; Oakland, California; San Francisco, California; and Minneapolis-St. Paul, Minnesota. Denver is currently implementing baseline assessments for its school district and city jails, with other institutions interested.

However, we contend that something is lost in eliminating the lengthy and inclusive process used in creating the GFPP for use in Los Angeles. Though the city has collected precursor data via a Food Vision (City of Denver, 2017), and sought input through meetings with a procurement subcommittee of the SFPC, the process has not been inclusive of regional farmers and ranchers or other key stakeholders. The challenges this creates are already evident in Denver as the city works to promote consensus around the adoption of the program. Here, we highlight two place-based sticking points: first, USDA organic as the "level 3" criterion (the highest level) for most commodities under the environmental sustainability value; and second, the awarding of points under the "animal welfare" category for reducing the total volume of animal products purchased. In both cases, challenges arise due to the blanket adoption of values or standards without enough regard to how their implementation will result in different impacts based on local context.

Much research has been devoted to comparing the soil health impacts of conservation tillage (a.k.a. no-till), which uses herbicides instead of mechanical tilling to kill existing vegetation and prepare ground for planting, to organic farming (Carr et al., 2012). Because most herbicides are banned in organic agriculture, it still relies heavily on conventional tillage (Luna et al., 2012). This can have negative effects on erosion potential, aggregate diameter, water-holding capacity, and, perhaps most significantly due to the ramifications for climate change, organic carbon in the soil (Luna et al., 2012). These effects can be exacerbated in drought-prone, semi-arid croplands such as those found in eastern Colorado (Knapp, 1983; Mikha et al., 2013). It is therefore doubtful that uniformly encouraging conversion to organic production practices, especially among dryland farming operations in eastern Colorado, will lead to improvements in environmental sustainability in the same way it might in different climates.

A second, more controversial, and somewhat perplexing example can be found under GFPP's animal welfare value. In order to be awarded full points, institutions have the option of either increasing their proportion of animal products certified as high animal welfare or reducing the total volume of animal products produced. Level 3 points in this case can include replacing 40% of the total volume of animal products purchased with plant-based proteins. Given that this target is under animal welfare, it appears to assume that reduced purchases, and therefore production, of animal products will lead to improved conditions for the remaining animals. The justification for this assumption is unclear. We cannot help but wonder about the composition of the stakeholder group that formulated GFPP, where it appears that representatives from animal agriculture were few while those from animal rights group were many. While this may have been suitable for southern California, it is fair to conclude that a stakeholder group representative of the Colorado food system, where the beef industry is a key stakeholder and vast areas of land are only suitable, agriculturally-speaking, for livestock production, would arrive at a different approach to improving animal welfare.

There are many other examples of local concerns about GFPP, both related to elements within specific standards and the program structure overall. For example, in focus groups with Colorado ranchers about GFPP, many have expressed confusion about elements of the Animal Welfare Approved standard, such as weaning of calves at 8 months of age, which they thought to be unrelated to welfare, and prohibitions of electric prods, which they said improve cattle welfare when used judiciously in dangerous situations. Additionally, many objected to the prohibition on branding of cattle, both from a socio-cultural and practicality perspective. In our view, whether the ranchers or the standards are correct on these matters is immaterial; rather, because the ranchers played no role in creating the standard and find some elements to be non-sensical, the chances of broad-scale adoption, and thus broad-scale change, are greatly diminished. We believe that this "prescriptive to a fault" characteristic of many standards does more harm than good.

Additionally, the Denver SFPC's procurement committee has advocated for adding a sixth value category of food justice and racial equity to the program, but GFPP does not allow this. Indeed, it appears that the GFPP is almost entirely inflexible when it comes to local adaptation. This is for practical reasons; the Center works with participating municipalities and institutions to monitor progress toward GFPP goals. If each participating GFPP institution had different standards, it would increase costs associated with monitoring and verification. This is how the key innovation of GFPP—using broad, well-known standards—becomes a liability. If the standards are not locally adaptable and if the GFPP is inflexible in assigning points to the standards, as has been indicated both in general documentation and specific communications, then the program is not suited to the particulars of place and the democratic processes that are essential to integrate if we are to truly improve agricultural sustainability.

Toward Place-Based, Democratic Standards

Community Readiness

An important place-based characteristic is a community's "readiness" for policy interventions. Community readiness is generally thought of as a community's capacity for change. The community readiness literature has looked especially closely at the implementation of prevention (e.g., drug, obesity, crime) programs to understand the unevenness of their success across communities. It indicates that there is more to a program's success or failure than whether it was poorly planned and implemented or lacked sufficient funds to carry out goals. In many cases, failure is attributable to the prevention programming not receiving sufficient community support, with some programs being met with outright resistance (Hawkins et al., 1992; Donnermeyer et al., 1997).

In cases of program failures, the community might not be ready to accept that there is a "problem." Alternatively, there may be disagreement over the specifics of the problems—e.g., is it a drug problem or, say, a mental health or economic problem (or some mixture of all of the above). Or perhaps the community lacks social cohesiveness and distrusts local and governmental institutions, in which cases community-based prevention programs are destine to failure until these deep sociological problems are tended to.

Carcasson and Sprain (2016, p. 42) outline a number of things communities need to be able to do when seeking to create potentially system-changing interventions. According to their vision of community readiness, communities must have the ability to afford:

(1) Broad, diverse engaged audiences who are exposed to quality information and a willingness to consider multiple perspectives;
(2) Genuine opportunities for those audiences to work through the inherent tensions, trade-offs and paradoxes of issues;
(3) Ongoing collaborative and complimentary actions that allow for productive "responses" to those tensions.

We mention this literature as a reminder that even well-planned and financed policies will fail if a community is not ready to accept the interventions or if they are insufficiently resilient to work through the inevitable tensions and shocks that interventions bring. When considered in the context of place-based food standards, the community readiness literature teaches us that places also have varied assets and liabilities when understood from the perspective of elements like social, cultural, and economic capital. Whether communities can successful implement such standards are a function of those assets—their level of community readiness. The decision to start a process such as GFPP must therefore account for this across the area of potential impact—there may be instances where it is better to not begin than to do so without an understanding of capacity, especially given the fundamental importance of food.

Part of the challenge in the case of Denver, as well as many of municipalities enacting this type of policy, is that there is often not alignment in readiness across regions. Communities, such as Denver, must operate within the confines of their political authority, in this case the city and county. Seventy-one percent of food policy councils in North America operate at the county or sub-county (e.g., city) level (Bassarab et al., 2019). Yet, it is very unlikely that most counties, particularly those that are urban, can meet their own food needs. As an example, according to the latest Census of Agriculture, Denver County included 12 agricultural operations, none of which were over $100,000 in sales (USDA NASS, 2017). Accordingly, the possibility that Denver will meet its own institutional food demands is nil, and regional producers must be meaningfully incorporated into discussions before Denver is ready to begin the process of discussing values-based food procurement standards.

Putting Place Into Practice

A key shift in moving toward place-based, democratic standards is from an outcome-based to a process-based approach. In this we are informed and inspired by the literature on the benefits of collaboration in natural resource management. It is increasingly recognized that top-down, consultative approaches to difficult natural resource challenges often do not lead to positive long-term outcomes (Pretty, 2008). Instead, social capital is emerging as a key element in achieving lasting solutions, with process elements such as commitment, empathy, respect, transparency, and predictability perhaps as important as good science or financial resources (Wagner and Fernandez-Gimenez, 2008).

Because successful standards are built on trust, between the standard and both those being certified and those purchasing the certified products, this finding suggests an exciting pathway for a new kind of standard, one in which the process of creating the standard, rather than institutional authority, is what builds

TABLE 1 | Operationalizing place as practice: domains, boundaries, and flows.

Domain	Boundaries	Flows	Examples
Biophysical	What are the biophysical boundaries of this place?	What are the biophysical connections this place has with other places?	Water, biota, hills, air
Political	What are the politics and political boundaries of this place?	What are the politics and political connections this place has with other places?	Neighborhood, city, county, state boundaries; normative orientations toward how this place ought to be and how we get there
Economic	What are the economic boundaries of this place?	What are the economic connections this place has with other places?	Industries, labor, ownership, infrastructure
Socio-cultural	What are the socio-cultural boundaries of this place?	What are the socio-cultural connections this place has with other places?	Histories, identity, customs, attitudes, beliefs, values, norms

producer and consumer trust. Indeed, we assert that, absent a locally driven co-creative process, standards that rely on institutional authority to establish credibility gain the benefits of consumer trust without doing the work to ensure on-the-ground impact.

A shift toward process-oriented standards not only addresses the need for credibility, it also enables effective adaptation of standards across space and over time. Instead of existing as a set of inflexible prescriptions, a process-based standard for sustainable beef would instead support an iterative process for seeking gains in sustainability that are suited to place. This is not to suggest that "anything goes"—a set of transformative sustainability values and goals must be fundamental. However, the standard would not be prescriptive in determining how they are recognized and achieved but instead allow for the inherent creativity of people in place to determine that for themselves. This combination of transformative sustainability goals and locally adapted actions to achieve them prevents both bureaucratic overreach and local attenuation.

We have noted that, in addition to credibility, recognizability is a key component of successful standards. We contend that recognizability does not emerge from consistently prescriptive standards, but instead from a different kind of trust-building process between the consumers and the standard. This contention is supported by the significant literature on consumer perceptions of standards, which indicates that consumers generally have a poor understanding of what underlies different standards but instead respond to perceived quality, consistency, and clarity of the message (Becker, 2000; Codron et al., 2006; Abrams et al., 2010; Janssen and Hamm, 2012). Again, we are not suggesting something along the lines of "consumers will buy what we tell them to" but rather that the characteristics of interest to consumers are not inherent to broad, prescriptive standards. Indeed, they may reside more effectively within place-based, democratic, process-oriented standards, wherein the focus is on long-term outcomes rather than specific, esoteric production practices.

Finally, instead of ignoring tradeoffs, standards should acknowledge or even embrace them. For example, most sustainability standards ignore economic considerations for producers. Instead, it is assumed that increased product value will justify any expenses of transitioning to new production practices, based on the assumption that retail prices naturally and equitably translate to higher farm-gate prices, which may or may not be true depending on factors such as scale, commodity, location, and market channel (McBride and Greene, 2009). Even if a new certification does lead to increased farm-gate prices, it is still entirely possible that this may not justify the cost of the changes.

Instead of ignoring this potential reality, we suggest that standards should instead fundamentally integrate economic considerations. By embracing instead of ignoring potential tradeoffs, and building them into the standards, knowledge about potential economic challenges would be at the forefront for producers adopting new practices, and the standard could potentially play a role in transforming supply chains to more equitably distribute the food dollar. Numerous other potential tradeoffs should also be integrated, including among different environmental sustainability metrics, which are at times in conflict.

We suggest that operationalizing place as practice, something necessary to informing effective standards, must be an ongoing and iterative processes that values the bio-physical, political, economic, and socio-cultural dimensions of place. As an ongoing and iterative process, standards such as the GFPP must be thoroughly vetted and edited through engagement with stakeholders. As a way to stimulate collective engagement and action, and iterate how standards enact practices in place, we suggest the use of **Table 1** to stimulate conversation.

STARTING POINT FOR A COLORADO SUSTAINABLE BEEF STANDARD

Because we are proposing a place-based, democratic, and process-oriented approach to creating and applying sustainability standards, it is not appropriate to offer a prescription for a sustainable beef standard for Colorado. Instead, here we suggest a starting point for a more inclusive, just, and ultimately sustainable approach to achieving Denver's institutional purchasing goals. In doing so, we want to make clear that we recognize that this approach is likely to be more time-consuming and expensive. However, we also believe that it would also be more successful in the long run for all stakeholders, including urban consumers and rural producers.

We propose that a beef sustainability standard for Colorado be based on shared core sustainability goals arrived at through an inclusive multi-stakeholder process that is evidence-based. Especially on a topic as important as sustainability, disagreements among stakeholder are often driven by opinion rather than science-based evidence. On the other hand, we recognize that science sometimes fails to adequately account for complexity, social factors, and its own biases. Nevertheless, agreeing to base the conversation on evidence rather than opinion can assist in finding areas of commonality.

Though there are certainly examples of beef sustainability goals (e.g., from the U.S. Roundtable for Sustainable Beef), establishment of these goals in Colorado must include all significant stakeholders, including but not limited to consumer advocates, rancher organizations, environmental organizations, federal agencies, labor groups, and policy makers. Though there are significant differences in perceptions of the beef industry and sustainability among these groups, we are confident that an inclusive, democratic process can arrive at a set of shared fundamental goals.

As a reminder, these goals should not be prescriptive about practices, but rather agreed-upon outcomes such as reduced greenhouse gas emissions, improved ecological health on rangelands, or increased share of the consumer food dollar for ranchers. Even in Colorado, however, there is a wide array of production systems and great climatic diversity. We therefore suggest that this goal setting process be regionally segmented. In all likelihood, there will be shared goals among different regions, but it may be that different regions prioritize these goals differently. At the same time, it is important to recognize that boundaries and flows are more than biophysical, and that a reconstitution of current boundary paradigms may be beneficial. Because the overall project is driven by Denver, the realities of urban consumers and city policies should permeate each region's process.

These goals should be examined through the lens of the different domains, boundaries, and flows detailed in **Table 1**. While it is important to set ambitious goals, it is also essential to ground them in the realities of place. Doing so will enable a realistic conversation among the various stakeholders. We believe that this can also help to bridge an urban-rural divide that may appear intractable but, we suggest, can be surmounted by understanding the place-based realities of those different from us. At the same time, it is also important to anticipate and even respect irreconcilable differences.

At this point, with shared goals, buy-in from stakeholders, and growing social capital, any number of paths forward may emerge. It may be that the use of third-party standards, or even a set of such standards such as the GFPP, may be the most appropriate choice, particularly in this case where Denver's goals extend far beyond beef. On the other hand, it is impossible to predict what this process, broadly applied across the food system, would lead to. What we are confident of is that it is much more likely to lead to the lasting systemic change that is necessary if we are to address the tremendous challenges facing agriculture and the food system.

AUTHOR CONTRIBUTIONS

All authors contributed equally to conceptualization and writing of the work.

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With Power Comes Responsibility – A Rangelands Perspective on Forest Landscape Restoration

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Tree planting has long been promoted to avert climate change and has received renewed impetus in recent years with the Bonn Challenge and related forest restoration initiatives guided by the forest and landscape restoration (FLR) framework. Much of the focus for reforestation and afforestation is on developing countries in Africa, Asia and South America, where large areas of rangelands in drylands and grassy biomes are portrayed as "degraded," "unused," and in need of more trees. This perception is rooted in persistent theories on forests and desertification that widely shaped colonial policy and practice and remain influential in today's science-policy frameworks. From a rangelands perspective, the global FLR thrust raises two main concerns. First, inappropriate understandings of the ecology of drylands and grassy biomes encourage afforestation, grazing restriction and fire suppression, with negative impacts on hydrology, carbon storage, biodiversity, livestock production and pastoral livelihoods. Second, their target-driven approach requires large-scale afforestation and massive funding to achieve. Nearly half of the area pledged to the Bonn Challenge is in fact destined for forestry and other commercial plantations, which threaten pastoral livelihoods and cause ecological damage while having very limited potential to mitigate climate change. As the officially endorsed framework of the Bonn Challenge and related global restoration initiatives, FLR has become a powerful instrument for guiding global restoration efforts and funding. Its proponents have a responsibility to ensure that the framework is evidence-based and underpinned by appropriate ecological models for different ecoregions.

Keywords: savanna, rangeland, pastoralism, grassland, climate change, Bonn Challenge, afforestation, drylands

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INTRODUCTION

In July 2019, Ethiopia was celebrated worldwide for planting over 350 million trees in a single day. "Afforestation is the most effective climate change solution to date and with the new record set by Ethiopia, other African nations should move with speed and challenge the status quo," responded the Director of the United Nations Environment's Africa Office (United Nations Environment Programme (UNEP), 2019). This example epitomizes the current momentum to promote large-scale tree planting as an urgent solution to climate change. The Bonn Challenge, a United Nations programme initiated in 2011 to restore biodiversity and mitigate climate change through restoration of degraded landscapes, has set targets of restoring 150 million ha (Mha) of deforested and degraded land by 2020, and 350 Mha by 2030. The Bonn Challenge has generated several offshoots, including the African Forest Landscape Restoration[1] initiative to restore 100 Mha of degraded forest landscapes in Africa. These massive forest restoration targets raise important questions about the implications for the world's drylands and grassy biomes and the rangelands they support.

The Bonn Challenge and related initiatives officially adopt forest landscape restoration as their guiding framework. Forest landscape restoration (FLR) is "a process that aims to regain ecological functionality and enhance human well-being in deforested or degraded landscapes[2]". From this original broad conceptualization, different constructs of FLR have emerged that reflect the knowledge, traditions and objectives of different disciplines including forestry, ecology and rural development (Mansourian, 2018). General FLR principles include the need to focus on landscapes with their complex socio-ecological and political dimensions, engage stakeholders and support participatory governance, restore multiple functions for multiple benefits, maintain and enhance natural ecosystems within landscapes, respond to local contexts using a variety of approaches, and manage adaptively for long-term resilience (Besseau et al., 2018; Bonn Challenge, 2020).

Despite this compelling win-win rhetoric of restoring ecological integrity, biodiversity and local livelihoods, the target-driven global forest restoration initiatives reflect an enduring, target-driven colonial legacy of forest and resource governance, as well as the progressive commodification of nature and top-down planning driven by international development agencies, national governments and commercial interests (Fairhead et al., 2012, Davis and Robbins, 2018). From a rangelands perspective, two particular concerns stand out.

First, the framework is explicitly forest-centered and targets "degraded" and "deforested" land[3] for "forest restoration." In fact, drylands and grassy biomes are ancient and have formed the resource base of pastoral and agropastoral populations for millenia (Davis, 2016; Bond et al., 2019). Their restoration requires approaches that maintain their structure and function as disturbance-adapted, open ecosystems (Bond, 2019). The strong forest-centered ideology underpinning FLR has a long and unacknowledged history rooted in centuries-old theories on the causes and effects of deforestation and desertification, which have widely shaped colonial policy and practice and remain influential today (Davis, 2016). This has had detrimental consequences for rangelands and pastoralists, which the current FLR initiatives uncritically perpetuate.

Second, achieving the ambitious targets set by the Bonn Challenge and its offshoots requires large-scale afforestation (i.e., the planting of trees where they did not previously occur, as distinct from reforestation of areas historically covered by forest). Currently used definitions of "forest" allow plantations to be included as forest restoration (Chazdon et al., 2016), and available data on country pledges show that nearly half the land pledged for FLR is in fact earmarked for plantations, in most cases with fast-growing exotic species (Lewis et al., 2019). Commercial forestry plantations typically provide a fraction of the ecosystem services of the natural vegetation they replace (Crouzeilles et al., 2017; Lewis et al., 2019) and they can negatively impact on local livelihoods when they target and appropriate land used by local people for food production (Fairhead et al., 2012; Morecroft et al., 2019).

As the approach officially espoused by the large-scale restoration drives, forest landscape restoration has become a powerful framework for guiding restoration globally. Its proponents thus have a responsibility to ensure that the guidance it provides addresses these important shortfalls to avert ecological and socio-economic damage on a massive scale.

RANGELANDS AND OPEN ECOSYSTEMS: UNDERVALUED AND NEGLECTED

Rangelands occur over a wide range of vegetation types and form the main land use in the world's drylands, shrublands, grasslands, savannas and open woodlands, the world's vast and ancient open ecosystems (Bond, 2019). Livestock play an important role in these vegetation types due to their ability to convert non-human edible feed into useful products, and their mobility, which allows pastoralists to make use of scarce and dispersed resources (Blench, 2001; Ayantunde et al., 2011; Hoffmann et al., 2014). Livestock production is estimated to contribute at least 40% of the global agricultural output and supports the livelihoods of nearly 1.3 billion people (Steinfeld et al., 2006). Where official statistics are available, they show that pastoralism contributes significantly to national gross domestic product (Johnsen et al., 2019). Livestock provide approximately 26 percent of human global protein consumption and 13 percent of total calories, as well as essential micronutrients (Hoffmann et al., 2014). Owning livestock reduces the prevalence of severe food insecurity and ensures higher diet diversity across a range of countries in sub-Saharan Africa (Fraval et al., 2019).

Extensive pastoralism is the most ecologically appropriate and sustainable use of drylands and grassy ecosystems (Veldman et al., 2015b; Behnke and Mortimore, 2016; Sayre et al., 2017). Pastoral land use in these ecosystems has adapted to this high highly variable and unpredictable resource base through mobility, opportunism and reciprocity, and the inherent resilience and adaptability of pastoralism make it likely to emerge as an increasingly important land use under climate change (Blench, 2001; Boone et al., 2018). Given appropriate support, rangelands can contribute to sustainable, climate-resilient diversified farming systems (Sayre et al., 2012).

Extensively managed grasslands have a high per-hectare value of ecosystem services, comparable to that of temperate forests, and they provide an estimated quarter of the ecosystem services provided by terrestrial biomes (De Groot et al., 2012; Costanza et al., 2014; Bengtsson et al., 2019). Grassy biomes store up to a third of the world's carbon in their soils (Parr et al., 2014), and grazing lands contribute significantly to global carbon sequestration (Conant, 2010; Henderson et al., 2015). Grasslands are better suited than many forest types to storing carbon reliably under increasingly hot and dry climates, which make forests

[1] https://afr100.org
[2] http://www.forestlandscaperestoration.org
[3] www.bonnchallenge.org

vulnerable to die-back and wildfires (Dass et al., 2014). Restoring them is also relatively cheap and has the highest benefit to cost ratio of all the world's biomes (de Groot et al., 2013).

Despite their ecological and economic importance, drylands and grassy biomes are undervalued and underrepresented in research and policy (Parr et al., 2014). Temperate grassland is the most threatened and least conserved biome globally (Davis et al., 1995; Hoekstra et al., 2005), and conservation efforts are biased toward forests even where grasslands are biodiversity hotspots (Ambarlı et al., 2016). For the tropics, far less literature exists on the diversity and conservation of grasslands and savannas compared to forests (Bond and Parr, 2010). The global extent of grassy biomes remains poorly documented, and a widely used map of the world's terrestrial biomes (Olson et al., 2001) misclassifies many areas of grassy biomes (Veldman et al., 2015b).

Rangelands and the pastoralists they support are similarly neglected in literature and policy. Global estimates of the extent and distribution of rangeland are highly variable due to the use of imprecise definitions (Phelps and Kaplan, 2017), and a tendency to map rangelands as a "residual category" of land that is not forest, cultivated or urban (Sayre et al., 2017). Data on agriculture, livestock and forestry are inadequate for informing policymaking on rangeland-based livestock systems (Johnsen et al., 2019). Rangelands have long been marginalized and under pressure from conversion to other land uses, due to their lower economic value compared to cropping, conservation, residential development and mining (Sayre et al., 2013; CELEP, 2018).

Undervaluing rangelands and portraying them as unused and degraded has led to a lack of resources for studying, protecting and monitoring rangeland resources, despite the pressing need to understand them as climates continue to change (Boone et al., 2018; Johnsen et al., 2019). Incomplete knowledge of their nature, extent and location means that appropriate targets cannot be set for their restoration and protection (Phelps and Kaplan, 2017).

DRYLANDS AND GRASSY BIOMES: MISUNDERSTOOD ECOLOGIES

Open ecosystems span a wide gradient from semi-deserts to mesic savanna woodlands and are functionally distinct from forest (Bond, 2019). For the purpose of this discussion, I use the terms "drylands" and "grassy biomes" to represent two intergrading categories of open ecosystems that span a continuum of ecological dynamics.

Drylands are arid and semi-arid areas that have been described as disequilibrium systems characterized by high climatic variability and loose coupling between herbivore population dynamics and vegetation productivity over large areas (Behnke and Scoones, 1993, Ellis et al., 1993). Their vegetation is not strongly controlled by herbivory or fire and the primary production of the herbaceous layer is highly variable and predominantly driven by rainfall (Archibald and Hempson, 2016). Under traditional pastoralism, the potential for degradation in these systems is low as their erratic rainfall and primary production limits the extent to which livestock numbers can build up to levels sufficient to have a strong feedback on the vegetation (Ellis and Swift, 1988, Behnke and Scoones, 1993). However, the artificial provision of watering points and supplementary feed las led to rangeland degradation in drylands by increasing the availability of dry season key resources, thus increasing and stabilizing livestock populations and reducing their mobility (Illius and O'Connor, 1999, 2000; Vetter, 2005).

Drylands have a long history of being misinterpreted as degraded and desertified (Behnke and Mortimore, 2016; Davis, 2016). The notion that drylands are the result of deforestation by nomadic pastoralists, which resulted in their climate becoming arid, was widely held in the 19th century (Davis, 2016). The solution was "reforestation" and other interventions such as irrigation to "green" the deserts. These actions have often caused salinization of soils, lowering of water tables, and invasion of fast-growing exotic tree species such as *Prosopis*. Ironically, more often than not the "solution" to the resultant resource degradation consists of more cycles of the same misguided interventions (Davis, 2016).

The grassy biomes include semi-arid, subhumid and mesic grasslands and savannas. These more mesic rangelands have stronger resource-consumer coupling than drylands and support bigger, more stable agro-pastoral populations. Large parts of the grassy biomes occur in seasonal climates with enough rainfall to support closed-canopy vegetation (thickets or forest), where they are often found occupying the same landscape in two-phase mosaics. The open-canopy structure of savannas is maintained by grass-fuelled fires and browsing (Bond, 2019). Because of their higher (potential) tree cover, many savannas are misclassified, mapped and managed as forest, even though forest and savanna have fundamentally different ecological dynamics, reflected in distinct species assemblages with different functional traits (Ratnam et al., 2011; Veldman et al., 2015a).

Since large areas of savannas are misclassified as degraded forest, they are targeted by inappropriate restoration and fire suppression policies that cause large areas of savannas to be lost through woody encroachment, forest expansion and plantation forestry (Veldman et al., 2015c; Ratnam et al., 2016; Joshi et al., 2018; Buisson et al., 2019; Kumar et al., 2020). Woody encroachment is a widespread global phenomenon that leads to substantial losses in livestock productivity in rangelands (Archer et al., 2017; Stevens et al., 2017; Venter et al., 2018). Afforestation and encroachment by native and exotic woody species lead to loss of biodiversity and ecosystem services in grassy biomes, including carbon storage (Guo and Gifford, 2002), streamflow and groundwater recharge (Jackson et al., 2005; Honda and Durigan, 2016; Fahey and Payne, 2017; Zastrow, 2019) and grazing for livestock and wildlife (O'Connor et al., 2014; Bond et al., 2019). The faunal and floral diversity of grassy biomes is rapidly lost under the shade of closed-canopy woody vegetation, and extremely slow and difficult to restore (Ratnam et al., 2011; Zaloumis and Bond, 2011, 2016; Parr et al., 2014).

Colonial policies widely promoted "reforestation" of grassy biomes to "restore" their climate and productivity, and these ideas and practices are still prominent in FLR today. As in the drylands, this is a legacy of colonial interpretations of these landscapes rooted in 19th century European understandings of vegetation ecology (Joshi et al., 2018; Pausas and Bond, 2019; Kumar et al., 2020). Forest "restoration" often involves fast-growing exotic tree species (including eucalyptus, pine and wattle) that have been the source of well-documented species invasions and other ecological impacts. Because of their higher productivity, the more mesic grassy biomes are the areas predominantly targeted for large-scale plantation forestry, carbon sequestration and climate mitigation projects.

APPROPRIATE METHODS FOR RESTORING OPEN ECOSYSTEMS

Restoration of natural and semi-natural terrestrial ecosystems has important potential to deliver climate change mitigation and other ecosystem services (Morecroft et al., 2019). Restoring savannas and grasslands improves carbon storage in soils, protects water resources, and reduces the risk of catastrophic fires (Archibald et al., 2013; Buisson et al., 2019; Morecroft et al., 2019; Wigley et al., 2020). To regain ecological functionality and ecosystem services in degraded grassy biomes requires restoring native grass cover, the removal of woody plants and the application (and often re-introduction) of appropriate fire and herbivory regimes (Buisson et al., 2019). These are fundamentally different from the methods used to restore forests, which require protection from fire and herbivory to build up tree cover.

In many areas of low tree cover, agroforestry, woodlots and other forms of tree-based restoration are important for meeting the food, forage and energy needs of increasingly dense populations. The fast-growing and drought-tolerant exotic species often chosen for this purpose can have unintended negative effects, however, such as lowering water tables and causing salinization where their water use and transpiration exceeds rainfall (Wang and D'Odorico, 2019; Zastrow, 2019). Well-intentioned but ill-conceived interventions to plant trees in rangelands have led to substantial and long-term losses in ecosystem services, especially when introduced species become invasive (DiTomaso et al., 2017).

In more mesic areas with high population pressure, some savannas and woodlands have lost tree cover through shifting cultivation and harvesting of wood for timber, firewood and charcoal (Shackleton et al., 2005; Matsika et al., 2012; Mograbi et al., 2017). Planting trees is not always necessary to compensate for localized loss of tree cover, however, especially in productive ecosystems where tree cover and biomass can recover rapidly. In the miombo woodlands of southern Africa, shifting cultivation and wood harvesting have led to a loss in tree cover and degradation, but the effects of this on carbon storage at the regional scale are offset by coppicing and increased woody cover in less intensely used areas (McNicol et al., 2018). Miombo woodlands are resilient to high levels of disturbance, as they have historically had high densities of elephant and frequent fires (Hempson et al., 2015; Osborne et al., 2018). This suggests that passive or assisted regeneration of natural vegetation is an effective way to restore carbon storage functions at the landscape level. However, promotion of "passive restoration" or "natural regeneration" can be problematic if it leads to fire suppression and grazing exclusion in open ecosystems that have co-evolved with these disturbances and need them to retain their ecological integrity and productivity.

AN UNHEALTHY OBSESSION WITH AFFORESTATION TARGETS

One of the conspicuous features of the current FLR drives is the foregrounding of ambitious targets, which are mirrored in many national initiatives such as the National Mission for a Green India. Afforestation targets have a long history going back to colonial forestry in the 1800's, which served the dual aims of providing enough timber and supporting "civilization" by stabilizing climate, increasing rainfall and improving soil fertility in the tropical colonies (Davis, 2016; Davis and Robbins, 2018). This was epitomized by the concept of the *taux de boisement normal* – the percentage of forest cover in any territory required by a civilized nation, regardless of its climate or other biophysical characteristics. This influential concept in French forestry of the late 1800's had its roots in desiccation theory, the notion that deforestation causes aridification and that reforestation increases rainfall, which had become widely accepted in Europe by the middle of the 19th century. Contemporary forest targets and their rationale (to mitigate climate and improve agricultural productivity) have changed remarkably little from their colonial origins (Davis and Robbins, 2018). They are now also based on the fallacy that a given amount of forest cover can store enough carbon to significantly mitigate climate change (e.g., Bastin et al., 2019a), a claim that has been widely refuted (e.g., Bond et al., 2019; Lewis et al., 2019; Veldman et al., 2019).

The current targets have gained additional power and apparent credibility by their presentations as digital maps based on scientific analysis of "global restoration potential." The two publicly accessible sets of maps intended to guide forest restoration globally are those published on the websites of the World Resources Institute[4] (WRI; Laestadius et al., 2011; Minnemeyer et al., 2011) and the Crowther Lab at the ETH Zürich[5] (Bastin et al., 2017, 2019a). Both sets of maps present restoration potential and opportunity in areas where tree cover is below that which is possible based on climate alone, which includes most mesic savannas globally. In Africa, areas identified as suitable for reforestation overlap significantly with the distribution of grassy ecosystems, which are important centers of vertebrate diversity and support the most important rangeland areas (see Figure 1 in Bond et al., 2019). Similarly, the WRI maps define "degradation" as a tree cover deficit relative to climatic potential, which automatically results in fire-maintained savannas as being mapped as degraded (Veldman et al., 2015a,b, 2019; Griffith et al., 2017). These maps reinforce the idea that these open ecosystems and the rangelands they support are anthropogenically created or modified "anthromes" (Ellis and Ramankutty, 2008; for a critique, see Sayre et al., 2017).

The definition of "forest" as any area > 0.5 ha with > 10 % tree cover (FAO, 2010) is similarly problematic. Its origins

[4]https://www.wri.org/resources/maps/atlas-forest-and-landscape-restoration-opportunities

[5]https://www.crowtherlab.com/maps-2/

can be traced to a time when timber management was the prevalent objective of forestry and it was designed to be useful for assessing wood harvesting potential (Chazdon et al., 2016). It was not intended to be used for planning and monitoring forest restoration and it has serious limitations for this purpose, as it does not distinguish between plantations and old-growth, recovering or degraded forest (Putz and Redford, 2010; Chazdon et al., 2016). Definitions of forest that do not distinguish forest from plantation allow natural forests to be severely degraded or replaced by plantations while technically remaining "forests" (Sasaki and Putz, 2009). For grassy biomes it has equally serious consequences, as large areas of savanna with naturally sparse tree cover are incorrectly classified and mapped as forest and thus in need of "reforestation."

The areas of grassy biomes misclassified as opportunities for tree planting are vast: some 1 billion ha, or 40%, of the areas mapped as "forest restoration opportunity" in the WRI maps are grassy biomes (Veldman et al., 2017). The dryland areas additionally identified by Bastin et al. (2017, 2019a) as having the potential for increased tree cover substantially increase this total. The powerful but misleading message these maps convey is that massive areas of grassy biomes are degraded and represent an opportunity for afforestation to mitigate climate change, with potentially devastating consequences for ecosystem services and biodiversity.

A RESPONSIBILITY TO PROVIDE ACCURATE GUIDANCE: HOW DOES FLR MEASURE UP?

There has been mounting criticism of the misleading message of the WRI's map of forest restoration opportunities (Veldman et al., 2015a,b; Bond, 2016) and the Crowther Lab's maps of tree restoration potential (Griffith et al., 2017; Veldman et al., 2017, 2019; Bond et al., 2019). The disingenuous response has been that the maps are not to be seen as prescriptive of what needs to be done, but rather what is possible in the absence of human disturbance. Their proponents argue that they need to be interpreted with caution, and that they merely provide large scale guidance that needs to be followed up with finer-scale planning, which is the responsibility of each country or region (Laestadius et al., 2015; Chazdon and Laestadius, 2017; Bastin et al., 2019b). However, if an area is mapped as "deforested" or "degraded" by experts, and at the same time there is pressure to pledge "ambitious" targets toward the Bonn Challenge and related initiatives (with strong positive publicity and promises of funding for countries that pledge large areas toward the targets), then how is one to interpret such maps? Those in charge of local assessments are unlikely to query their message since the maps are presented on authoritative websites, endorsed by reputable international development and conservation organizations, accompanied by articles published in leading journals, and their authors come with impressive credentials [as pointed out by Veldman et al. (2015b)].

Rangelands and grassy biomes are conspicuous omissions in the text of websites of the Global Partnership on Forest and Landscape Restoration, the Bonn Challenge and its offshoots such as AFR100. Document searches for the terms "grass," "grassland," "savanna," "grazing," and "rangeland" returned little or nothing in the documents guiding the planning, implementation and financing of FLR (PROFOR, 2011; IUCN and WRI, 2014; Berrahmouni et al., 2015; FAO UNCCD, 2015; Ding et al., 2017; Stanturf et al., 2017; Besseau et al., 2018). None of these sources recognize rangelands as a widespread and important land use, or caution that grasslands and savannas are areas that should be avoided for afforestation. A review of FLR projects in Africa turned up no examples of grassland restoration, but several instances of afforestation, including in savanna vegetation (Table 3 in Djenontin et al., 2020). A document reflecting on 13 years of successful FLR in central Madagascar mentions only tree planting and fire protection among the methods used, despite a third of the project area being in savanna vegetation (Mansourian et al., 2018). The handbook on the Restoration Opportunity Assessment Methodology equates restoration with planting trees and provides no caution against afforestation of open ecosystems (IUCN and WRI, 2014). A case study in this handbook illustrating the process in Rwanda makes it clear that no biome is exempt from afforestation: the highest priority actions identified for the eastern savannas were the creation of new large-scale commercial forestry plantations and woodlots.

The only criteria used to exclude an area from forest restoration are related to unavailability – urban areas, croplands and settlements of high human density (IUCN and WRI, 2014). Both the WRI and the Crowther Lab maps follow a similar logic. An important consequence of this logic is that afforestation will target more sparsely populated and "unused" areas – and this will affect large areas of untransformed grassy biomes used as rangelands. The WRI maps the ancient grasslands and savannas in the interior of Madagascar (Bond et al., 2008) as deforested or degraded, with low population density, and hence presenting forest restoration opportunity. While it is unlikely that the producers of the maps intended to give carte blanche to developers to turn large areas into biofuel or forestry plantations, if investors and the government agencies responsible agreed that such a venture would be in the country's best interest then who would stop them, and on what basis? If old-growth grasslands and savannas are to be "no-go" zones for afforestation, they need to be mapped, and documents guiding FLR needs to provide the correct guidance on how to restore them appropriately.

PLANTATION FORESTRY MASQUERADING AS ECOSYSTEM RESTORATION

Brancalion and Chazdon (2017) propose four principles to guide tree planting schemes focused on carbon storage and commercial forestry in the tropics in the context of FLR. Tree planting should enhance and diversify local livelihoods, avoid the transformation of tropical grasslands and savannas, promote landscape heterogeneity and biodiversity, and distinguish residual carbon stocks from those derived from reforestation and afforestation. By these criteria, large-scale monoculture plantations are not desirable as the cornerstone of FLR, and afforestation of grassy biomes should be avoided.

If this is what the Bonn Challenge is promoting, there should be no need for concern that old-growth grassy biomes will be lost to large-scale afforestation. However, examination of countries' reports on national pledges to the Bonn Challenge shows that almost half of the pledged area is set to become commercial plantations of trees such as eucalyptus, acacia, cacao and rubber (Lewis et al., 2019). If these proposed restoration plans are implemented, Lewis et al. (2019) estimate that the extent of plantations in the tropics and subtropics would more than double, increasing by 157–237 Mha. While a few countries target most of the area pledged for regeneration of natural forest (e.g., Chile, Lao, Mexico, and Vietnam) or agroforestry (Burkina Faso, El Salvador and Rwanda), countries such as Brazil, China, the Democratic Republic of the Congo, Ghana, Kenya, Uganda and Zambia plan to predominantly use plantations (Lewis et al., 2019). Most of these last-mentioned countries have large expanses of grassy biomes and rangelands, and they include the countries with the biggest areas pledged to restoration.

Plantations are necessary to meet global demands for timber and other wood products, but like commercial agriculture and urban expansion they represent a trade-off against many ecosystem services (such as water, forage, biodiversity) rather than yielding synergistic outcomes (Morecroft et al., 2019). There has been growing criticism of representing afforestation with forestry plantations as forest restoration, since plantations have less value for biodiversity or carbon sequestration compared to naturally regenerating forests (Chazdon and Guariguata, 2016; Crouzeilles et al., 2017). Monocultural tree plantations sequester 40 times less carbon than naturally regenerating forests when one takes into account tree harvesting (Lewis et al., 2019), and conversion of grassland to forest leads to losses in soil carbon stocks (Guo and Gifford, 2002). In degraded Mediterranean rangelands, grazing management yielded greater ecosystem services than afforestation (Papanastasis et al., 2017).

Forest restoration can make a valuable contribution to improving livelihood diversity, as natural and restored forests contribute to diet quality directly and via agropastoral and income pathways (Baudron et al., 2019). Large-scale forestry plantations, on the other hand, often compete with food production and other livelihood activities and reduce resilience by emphasizing a narrow bundle of market-related income streams (Ota et al., 2020). Large scale carbon forestry and bioenergy projects have been associated with land grabs that serve interests outside the affected area and lead to a loss of local access to natural resources and land (Lyons and Westoby, 2014, Busscher et al., 2020; Blum, 2020). Rangeland areas are particularly vulnerable to such appropriation, due to tenure insecurity and a widespread perception that pastoralism is an inefficient form of land use in degraded or "idle" landscapes (Blench, 2001; Cotula et al., 2009; CELEP, 2018). International investment for commercial plantations, carbon storage and other "green" initiatives show clear continuities from the colonial era in the appropriation of land, resources and access rights from their prior users for commercial gain (mining, large-scale agriculture, plantations) or in the name of conservation and halting land degradation (Cotula et al., 2009; White et al., 2012). Contemporary "green grabbing" involves an even greater variety of actors – including state agencies, national elites and a variety of private investors and consultants – who are "more deeply embedded in capitalist networks, and operating across scales, with profound implications for resource control and access" (Fairhead et al., 2012, p. 239).

AN OPPORTUNITY TO MAKE LANDSCAPE RESTORATION MORE INCLUSIVE, JUST AND EQUITABLE

The current global impetus to promote ecosystem restoration (Suding, 2011; Suding et al., 2015; IPBES, 2018) provides an opportunity to bring rangelands and grassy biomes onto the global restoration agenda. At the same time, one needs to interrogate the scientific and political-economic basis for the restoration agenda itself, with its uncritical perpetuation of target-driven forest planning and the logic of "the economy of repair" (Leach et al., 2012), which allows the problems created by emissions in developed countries to be "solved" by appropriating land and planting trees in developing countries.

To achieve an equitable, socially just and ecologically sound restoration agenda in rangelands, the following should be priorities.

Raise awareness of open ecosystems and rangelands. The misconception that drylands and grassy biomes are degraded forest continues to form the basis of major international programmes that address land degradation and climate change. These "pathological ecologies" (Davis and Robbins, 2018) continue to be transmitted to new generations of scientists and policymakers through outdated university and training curricula and postgraduate training. Breaking this "chain of transmission" will require a concerted effort at all levels, including decolonising of school and university curricula and lobbying to represent open ecosystems, rangelands and the interests of local land users in the major science-policy platforms that inform FLR[6]. It will also require efforts to capture the public's imagination with messages and imagery of drylands and grasslands as valuable, diverse and interesting, rather than degraded, fragile and desperate.

Strengthen innovative and strategic thinking and action around the future of rangelands. Pastoralism in many regions has proven to be resilient in the face of multiple pressures, such as fragmentation of rangelands, conversion of rangeland to other land uses, population growth, political marginalization, periods of severe drought and climate change (Galvin et al., 2008; Moritz et al., 2009; Sayre et al., 2013). Continued appropriation and afforestation of their seemingly "unused" and "degraded" land severely constrains the ability of pastoralists to continue their livelihood practices and to adapt to changing climates. Restoration and development in these regions should place the land and access rights of pastoralists and the need to support

[6]For example, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), which emphasizes social-ecological linkages, quality of life and diverse local knowledge (https://ipbes.net/conceptual-framework).

resilience locally over the need for storing carbon to ameliorate global climate.

Provide the right guidance. Instead of promoting scientifically unfounded targets for increasing tree cover, the documents guiding landscape restoration need to include clear guidelines on where planting trees is appropriate and where it is *not* advisable. These resources also need to provide information on appropriate restoration strategies for the grassy biomes, such as clearing exotic vegetation, using savanna species for restoration and agroforestry, restoring grassland function through appropriate grazing management and burning, and avoiding or reversing bush encroachment (Buisson et al., 2019, Temperton et al., 2019; Silveira et al., 2020).

Correct or replace the restoration opportunity maps. Rather than leaving each country to work out the distribution and appropriate management of different ecoregions themselves, a concerted effort should go toward providing accurate global maps that provide appropriate guidance. There also needs to be greater resistance to the current maps' implicit message that it is the responsibility of countries with "restoration opportunity" to fix a climate crisis they did not cause by making their land and resources available for carbon sequestration investments. Judging from the debates in the scientific literature, it seems highly unlikely that the maps' original authors and their institutes will change the maps or the message, although pressure to do so should continue. There is thus an urgent need to bring together ecologists, geographers and others with relevant expertise to produce and promote a more accurate suite of products.

As the officially endorsed framework of the Bonn Challenge and related global restoration initiatives, FLA has become a powerful instrument for guiding global restoration efforts and funding. The proponents and practitioners of FLR thus have a responsibility to include the existence, distribution, requirements and value of rangelands and grassy biomes in their message to the world. The continued resistance of FLR proponents to criticism of its arborocentric focus suggest that open ecosystems are indeed an "inconvenient reality for large-scale forest restoration" (Veldman et al., 2017), perhaps by reducing appetite for investment from sources interested primarily in offsetting carbon by planting trees. Hopefully this is not the case, and by including a greater diversity of ecologists and other stakeholders, FLR can be strengthened in promoting restoration of ecosystem function and biodiversity in all biomes while safeguarding the rights and livelihoods of local land users. This would be more in keeping with its original ethos than allowing it to be used as a vehicle for expanding commercial plantations to offset carbon emissions.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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Rangeland Ecosystem Service Markets: Panacea or Wicked Problem?

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Rangelands support nearly one-third of Earth's population and provide a multitude of ecosystem services. Land managers and society face increasing pressures to sustainably intensify rangeland food systems; therefore, the time is ripe for thoughtful approaches to simultaneously produce more food, provide economic opportunities for livestock-dependent communities, and enhance environmental benefits from rangeland ecosystems. Payments for ecosystem services (PES) programs have been put forth as potential mechanisms to maintain the quality and quantity of ecosystem services while enhancing economic viability of livestock operations. Free markets have long been proposed as solutions for mitigating trade-offs from ecosystem services that are not co-produced with livestock production; such markets have failed to emerge at the scale required to address global threats to sustainability. We highlight fundamental obstacles on demand and supply sides that challenge the concept of a market as a panacea; we do so through an interdisciplinary lens of fundamental economic underpinnings overlaid with a social survey of cattle producers' perspectives. Relevant to the demand side, we discuss the most significant impediments to development and function of non-bundled ecosystem service markets; on the supply side, we provide unique perspectives, using novel interview data from California rangeland cattle producers. Producer interviews highlighted substantial financial challenges threatening the economic sustainability of their operations. Among interviewed producers, 85% identified government regulations as the central threat to their livelihoods. Producers identified opportunities for enhancing enterprise sustainability via improved value and marketing of livestock goods co-produced with ecosystem services, participation in conservation easements, and improved connections with society. Only 11% of producers identified PES programs as future opportunities. When asked about willingness to participate in PES markets, 13% of interviewees indicated they would not, 45% were neutral, and 42% indicated they would consider participating. Interviewees stated trust in the market broker is key and they would be less willing to participate if there was government involvement. Ecosystem service markets—whether voluntary or

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non-voluntary—are likely not sustainable solutions to the complex social-economic-ecological dilemma ranchers and society face. Sustainability on working rangelands will require partnerships to co-develop strategies to build more equitable food systems and sustain these ecosystems.

Keywords: conservation, ecological tradeoffs, environmental markets, grazing, payments for ecosystem services, producer survey, sustainable livestock production

INTRODUCTION

Rangeland ecosystems such as grasslands and savannas cover ≈50% of the Earth's land surface (Lund, 2007). These diverse landscapes support nearly one-third of the world's population, and provide society with a multitude of material and non-material benefits, or ecosystem services, including food, fiber, water, and biodiversity (Havstad et al., 2007; Sayre et al., 2013). Global food demand is estimated to increase 70–110% from 2005 to 2050 (Tilman et al., 2011; Alexandratos and Bruinsma, 2012; Ray et al., 2013), and demand for animal-based protein is anticipated to increase substantially with income in developing countries (Tilman and Clark, 2014; Saitone and Sexton, 2017). Pressures to sustainably intensify rangeland food production systems will only escalate and, thus, the time is ripe for thoughtful approaches to simultaneously produce more food, provide economic opportunities for livestock-dependent communities, and enhance environmental benefits generated from rangeland systems (e.g., Capone et al., 2013).

Some posit that the up-cycling of rangeland vegetation to animal-based protein remains the only economically and ecologically sustainable food production system for vast rangeland landscapes (e.g., Alexandratos and Bruinsma, 2012), while others conclude that livestock grazing on rangelands leads to dangerous ecological trade-offs and declines (e.g., Eldridge et al., 2016) that make livestock production unsustainable in these ecosystems (e.g., Beschta et al., 2013). In fact, rangelands are complex systems in which agricultural and conservation synergies (e.g., Marty, 2005; Roche et al., 2012; Huntsinger and Oviedo, 2014) *and* trade-offs (e.g., Fleischner, 1994; Belsky et al., 1999; Thorburn et al., 2013) regularly occur; the challenge is overcoming *trade-offs* in a manner that is economically, socially, and ecologically sustainable. A suite of tested grazing best management practices (BMPs) exist to remedy many of the trade-offs associated with livestock grazing (e.g., Collins et al., 2007; George et al., 2011). However, implementing these BMPs can come at substantial added cost to livestock producers—the individuals best positioned to improve on-the-ground environmental outcomes.

Addressing these financial investments for individuals to enhance ecological conditions is an essential aspect of achieving sustainability on these working landscapes. In **Figure 1**, we illustrate three scenarios reflecting potential outcomes for traditional livestock market goods and other ecosystem services from the individual producer and societal perspectives. **Figure 1A** depicts a scenario with an unconstrained rangeland-based livestock production system where the singular focus of the producer is on maximizing profits from livestock goods (i.e., provisioning ecosystem services). In this scenario, producers' returns determine the effort (i.e., management practices) they invest. While this scenario is likely economically sustainable from the producers' perspective, trade-offs associated with the provision of other ecosystem services may occur. This is primarily a concern with ecosystem services that are not bundled (Raudsepp-Hearne et al., 2010; Spake et al., 2017) such that they are not co-produced with livestock production in space or over time. This singular focus causes the scale of net benefits derived from ecosystem services (**Figure 1A**) to tip toward traditional livestock goods at the expense of non-bundled ecosystem services. Depending on the severity and duration of the imbalance, this could lead to long-term ecological degradation that compromises environmental and economic sustainability such that the whole system collapses.

Regulations and policies are one approach to address trade-offs associated with agricultural production by requiring producers to implement BMPs. Scenario B (**Figure 1B**) illustrates the dilemma that may occur if producers are required to implement BMPs that address trade-offs for non-bundled ecosystem services (e.g., limit grazing in critical habitats) at the cost of the production of livestock goods. In this scenario, producers incur additional costs via labor (e.g., monitoring and management of livestock access to critical habitats), capital investments (e.g., fencing to exclude livestock from critical habitats), reduced livestock goods (e.g., fewer livestock due to loss of access to forage in critical habitats), and regulatory compliance (e.g., fees, monitoring, reporting, litigation). Ultimately, producers forgo some portion of their income from livestock goods and are unable to replace the loss with income from the enhanced, non-bundled, ecosystem services (e.g., clean water, carbon sequestration) that the regulatory interventions generate. While some in society might view this scenario as sustainable, producers are eventually crushed under the burden of additional costs, without commensurate financial return. The result (**Figure 1B**) tips the net benefits scale and eventually leads to collapse of the system (e.g., conversion of rangelands to alternative, more profitable uses) (Cameron et al., 2014). Regulatory programs are also vulnerable to shifting political agendas (e.g., repeal of laws and policies). While regulations certainly have a role to play in moving toward sustainability, we suggest that the current level of dependence is not sustainable over the long-term for society, livestock-dependent communities, or individual producers.

Increasingly, payments for ecosystem services (PES) programs have been put forth as potential mechanisms to match private

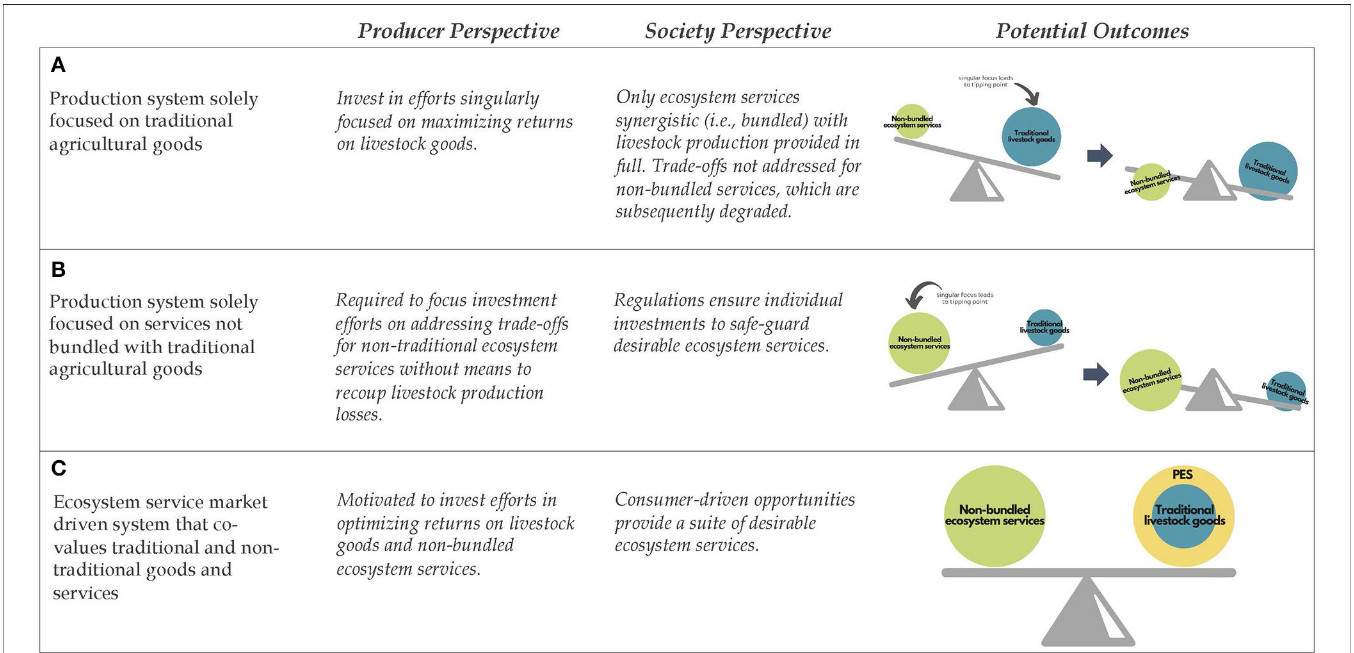

FIGURE 1 | Conceptual perspectives and outcomes of scenarios representing **(A)** unconstrained livestock production systems, **(B)** constrained production system with compulsory programs to address ecological trade-offs to livestock production, and **(C)** free ecosystem service markets to co-value and balance ecological trade-offs associated with provisioning livestock goods on rangeland ecosystems.

and public interests; some claiming them to be a solution where it is possible to maintain the quality and quantity of ecosystem services supplied while enhancing the economic viability of rangeland-dependent livestock operations. Payments for ecosystem services programs may manifest in a multitude of ways and forms including voluntary or regulatory, government-mediated or private, and incentive-based or market-based. However, in practice "...very few PES can be considered as pure markets" (Muradian et al., 2013). Rather, long-standing examples of PES are publicly funded cost-share programs (e.g., US Environmental Quality Incentive Program; AU National Landcare Program), which financially incentivize and offset costs (i.e., trade-offs) producers incur in implementing practices prescribed to enhance ecosystem services that are not bundled (Raudsepp-Hearne et al., 2010; Spake et al., 2017), or co-produced, with livestock production. These programs are substantial public investments (e.g., US Environmental Quality Incentive Program funding totaled USD $1.7 billion in 2017) that are dependent on factors such as national economic conditions and recession-driven budget cuts, efficiency in achieving actual additional conservation efforts (Claassen et al., 2013; Howard, 2020), and producer willingness to participate in voluntary subsidy programs (Lubell et al., 2013; Rolfe and Gregg, 2015).

Ecosystem service *markets* (one type of PES) have been proposed as a solution, perhaps a panacea, to fund the costs of mitigating trade-offs in a manner that is economically, socially, and ecologically sustainable for individual livestock producers, livestock-dependent communities, and society (e.g., Goldstein et al., 2011; Sayre et al., 2012; Yahdjian et al., 2015; Gordon et al., 2019). In this conceptual rangeland *ecosystem services production system* (**Figure 1C**), livestock goods, and other non-bundled ecosystem services are both able to generate value and society (i.e., consumers) can reward producers of ecosystem services (e.g., meat, fiber, clean water, habitat, carbon sequestration) in a market-based setting. Thus, investments in BMPs made by livestock producers, to address trade-offs and deliver non-bundled ecosystem services, can be profitable and consumers can influence the quantity and quality of ecosystem services generated by producers. In this scenario, payments derived from markets for non-bundled ecosystem services can increase net benefits derived by producers such that society's net benefits from non-traditional ecosystem services is balanced (**Figure 1C**) with the sum of producer net benefits from traditional livestock goods and the sale of ecosystem services from the rangeland-based operation. Eliminating the singular focus on any ecosystem service (e.g., maximizing livestock goods for traditional markets, regulation-dictated single species conservation) would allow for co-valuation and market-driven outcomes to sustainably balance producers' individual self-interests with society's demand for other, non-bundled services.

Some have credited the ecosystem service markets concept with bridging a gap between ecology and economics such that the full "worth" of ecosystems can be communicated to stakeholders (e.g., Chan et al., 2012). Since the time that ecosystem functions were defined, work has been ongoing to commoditize, value, and monetize ecosystem services (Silvertown, 2015). Certainly, there are some niche-type market transactions that have the potential to improve the sustainability of livestock producers and generate premiums for ecosystem services that are co-produced with livestock goods (i.e., provisioning services), albeit on a limited scale. The market for organic products is often considered the quintessential niche market in the US. However, a mere 0.14% of beef cow inventory in the US are certified organic. Clearly this and other niche opportunities are not at a sufficient scale to support livestock producers who are dependent upon hundreds of millions of acres of rangelands in the US alone.

Why then, have markets of sufficient scale for rangeland ecosystem services failed to develop as a stable, widespread solution (panacea) to the socio-economic-ecological crisis livestock producers and society face in conservation of non-bundled ecosystem services globally? In this paper, we highlight fundamental obstacles on both demand and supply sides, which make the creation of such a market a "wicked problem." Wicked problems typically involve multiple stakeholders with different perspectives, include complex interconnections, and have no single solution or one "right" answer; consequently, this wickedness defies normal problem-solving processes and attempts at resolution can reveal or even generate additional problems (Rittel and Webber, 1973; Balint et al., 2011).

To untangle the wickedness of this particular socio-economic problem, we address demand- and supply-side considerations for rangeland ecosystem service markets through an interdisciplinary lens of fundamental economic underpinnings overlaid with a social survey of livestock producers' perspectives. Relevant to the potential demand-side of the market, we discuss the most critical, and often overlooked, impediments to development and function of free ecosystem service markets for non-bundled ecosystem services; responding to recent reviews of a large literature that points to gaps in knowledge and understanding associated with this portion of the ecosystem service market interaction (e.g., Yahdjian et al., 2015; Sala et al., 2017). On the supply side of the market, we provide unique perspectives, using novel interview data, from a sample of 100 rangeland livestock producers across California, USA. This ultimately culminates in what we consider to be a long-overdue qualitative and quantitative analysis of the possibility of ecosystem service markets to contribute to the economic viability and ecological sustainability of rangeland-dependent communities at a large scale.

FREE MARKETS FOR RANGELAND ECOSYSTEM SERVICES—PANACEA OR WICKED PROBLEM?

What Is Required for a Market to Function Efficiently?

The supply of traditional livestock goods has historically been recognized as the primary value derived from rangelands (Havstad et al., 2007). These traditional ecosystem services (e.g., beef) are private goods (e.g., branded livestock), easily identifiable as units for sale and purchase (e.g., 1 pound of ground chuck), and are fungible (i.e., substitutable or interchangeable) such that supply and demand are represented concisely through market-based prices. Free markets are built upon a number of characteristics including freedom of choice, self-interest, competition, efficiency, private ownership, and limited government involvement. When one or more of these characteristics are not met, a market failure is said to occur; this is a situation where a market is not able to efficiently allocate goods or services. It is when we begin to consider non-bundled ecosystem services that complications arise with the development of a free market-based system for exchange. While challenges abound and many have been widely discussed (e.g., Kroeger and Casey, 2007; Redford and Adams, 2009; Goldstein et al., 2011), we focus on the most fundamental impediments: (i) many non-bundled ecosystem services are public goods and produce positive externalities, (ii) society lacks any incentive to pay for ecosystem services they receive for free—limiting demand for these services; and (iii) market intermediaries (e.g., brokers, certifiers, government) are necessary to verify the quality of the services being exchanged and mitigate transaction costs.

Is There Demand for Non-bundled Ecosystem Services?

In the context of economics and a market-based system, *demand* is defined as consumers' willingness and ability to pay for a good or service at all possible prices. Herein, lies the fundamental wicked problem—non-bundled ecosystem services (e.g., carbon sequestration, clean water, provision of wildlife habitat) are not private goods that the landowner or manager can sell. Rather, these are public goods and, as such, generate positive externalities (a type of market failure) that eliminates the need or incentive for consumers to purchase (i.e., demand) them in a market setting. Responses to this type of market failure are typically taxation and/or regulation (e.g., cap and trade). As such, an additional impediment to the creation of ecosystem service markets is the lack of existing regulatory infrastructure to generate demand and establish a price that reflects the true value of the service.

Public goods are defined as those that are non-excludable and non-rivalrous; goods or services where it is not possible to exclude individuals from consuming or benefiting from them and the consumption of the good or service does not take away from others consuming it as well. When public goods generate positive externalities, those who enjoy the service do so without compensating those individuals or entities that produce it. In fact, it can be argued that consumers take these non-bundled services for granted and only begin to care about their provision after they are perceived to be "degraded" (Goldstein et al., 2011). Society (consumers) *expects* these ecosystem services, but are unwilling to purchase them (i.e., create market demand) when they are able to consume them for free. The market failure (i.e., producers not receiving compensation for the services they supply) results in an under-provision of those services (**Figure 1A**). Simultaneously, existing public institutions and interventions fail to make up the growing gap between what society needs (or expects) and what is being provided (Lant et al., 2008).

This does not mean there are no consumers willing and able to compensate producers for practicing sustainable rangeland livestock production practices via the purchase of traditional livestock goods in niche markets or through direct to consumer sales channels; however, these exchanges are often focused on bundled services, and are woefully insufficient to create market demand of the scale required to address global threats to sustainability on rangeland ecosystems. Further, such niche markets often increase prices for traditional livestock goods thereby limiting food access for lower income population while increasing food insecurity (Gundersen and Ziliak, 2018).

What Is the Role of Market Intermediaries?

In order for exchange to occur between buyers and sellers, there must be a common understanding of the product or "unit" that is being exchanged such that its value can be established via negotiation. Yet, for many non-traditional ecosystem services it is extremely challenging to define the quantity and quality of a specific ecosystem service, both of which will affect market valuation. For this reason, many have asserted there will be large transaction costs (e.g., contract design, certification, monitoring) associated with the exchange of ecosystem services (e.g., Jacka et al., 2008; Gosnell et al., 2011). In the context of rangeland-based ecosystem services, transaction costs are likely to be relatively high given that the resource is maintained and controlled by a large number of diverse suppliers. For these and other reasons, intermediaries or brokers may be necessary to create market opportunities and facilitate information transfer among market participants (Davis et al., 2015). Brokers of services or market intermediaries could reduce transaction costs by acting as "aggregators;" purchasing and aggregating blocks or groups of services or service providers and selling them to buyers (Ribaudo et al., 2010). Market intermediaries may also be able to play a role in reducing the inherent informational asymmetries that exist between buyers and sellers (e.g., provide quality assurance services, verify that practices are in place on the ground, offering compliance certification; Ribaudo et al., 2010; Davis et al., 2015). Verification by a third party provides consumers with assurance that they are purchasing goods or services with the documented benefits they seek to purchase. In contemporary settings, where markets have yet to be created, government entities, and regulatory agencies are often considered logical intermediaries as they are often necessary for the market creation. This poses a challenge given that trust in the broker is critical in determining livestock producers' willingness to participate as suppliers in such markets (e.g., Davis et al., 2015).

LIVESTOCK PRODUCER PERSPECTIVES ON THE POTENTIAL OF ECOSYSTEM SERVICE MARKETS

We examine livestock producer responses to interview questions designed to gain insight into potential challenges and opportunities to the development and function of non-bundled, rangeland ecosystem service markets. First, we examine ranch structure given that operation characteristics fundamentally shape management decision-making and operators' capacity to consider and adopt new strategies (Prokopy et al., 2008; Lubell et al., 2013). We then explore producer-identified threats and opportunities to California's ranches and rangelands and the sustainability of their livelihoods. Finally, we specifically examine key questions about producer interests in ecosystem service markets, including whether or not there is evidence they would participate in such markets and under what conditions.

Interview Structure

As a case study, we present information we collected via semi-structured, in-person interviews of 100 experienced cattle producers from across California's 17 M hectares of grazed rangelands. Interviews were designed to gain insight into key questions regarding the potential for livestock producers to supply a multitude of rangeland ecosystem services to a market and their views on sustainability threats and opportunities. Using network-sampling techniques, interviewees were selected based on their rangeland management and ranching experiences and interests (Noy, 2008). Participants were identified through the University of California Cooperative Extension network. Interviews were led by the first author and were semi-structured using an interview guide containing questions about ranch operation structure, potential threats and opportunities for ranching and rangelands, and perspectives on ecosystem service markets. Interviews were audio recorded and transcribed. Interview text was analyzed using an iterative process of summarizing and organizing text passages into major themes using *a priori* and emergent codes (Knapp and Fernandez-Gimenez, 2009; Wilmer et al., 2018). The first and second authors conducted a peer-review process to cross-check interpretations and ensure validity of coding. These interviews are not a random sample and, therefore, are not intended to draw broad inferences; rather, this type of approach is useful for more in-depth explorations of experiences and perspectives. Participants were interviewed until no new information emerged from continued data collection (Gentles, 2015).

Ranch Structure

All interviewed livestock producers reported managing family-owned and operated rangeland-based cattle enterprises. Seventy-one percent were third or more generation owners and managers—suggesting a history of successful generational transfer and sustained production of livelihoods and livestock goods (Marshall and Stokes, 2014; Roche, 2016). Fourteen percent of interviewees identified as first generation owners and managers of ranching enterprises. This new segment of the livestock community is essential to recruit, but faces substantial obstacles to successfully entering ranching (Ahearn, 2011; Munden-Dixon et al., 2019).

Table 1 summaries the operational characteristics of the interviewees. The vast majority (99%) of rangeland cattle producers interviewed are engaged in a cow–calf operation where they maintain a permanent herd of brood cows that annually yield a crop of calves, which they either market upon weaning (71%) or retain ownership to market later (28%). One (1%) producer reported they only owned and managed yearling cattle they purchased from cow–calf operators. Rangeland-based cow–calf operations are the foundation of the beef industry in countries around the globe; for example, these

TABLE 1 | Operational characteristics.

Size of cow herd	Cow–calf operations ($n = 71$) Percentage of respondents (%)	Combined operations ($n = 28$) Percentage of respondents (%)	Size of stocker herd	Combined operations ($n = 28$) Percentage of respondents (%)
1–65 Head	8	0	1–40 Head	11
66–150 Head	23	11	41–150 Head	11
151–300 Head	27	25	151–500 Head	25
>300 Head	42	57	>500 Head	39

Percentages for combined operations do not sum to 100 because three combined operations failed to report cow numbers. The one operation that solely owned and managed yearling cattle is not included in the table.

operations comprise ≈90% of cattle enterprises in Australia. Among interviewed producers, ≈58% of cow–calf herds were reported to be 300 cows or less, and 47% of yearling herds were reported to be 500 head or less. This sample of rangeland cattle producers is reflective of the diversity of operational scales in the state. According to the U. S. Department of Agriculture's most recent Census of Agriculture (U. S. Department of Agriculture, 2017), 24% of beef cattle operations in California managed <100 cows, 34% of operations had 100–499 head, and the remaining 42% had operations with 500 head or more. Rangeland cattle producers in California manage extensive grazed systems with an average stocking rate of one cow (head) to 37 acres (Roche et al., 2015a). Common grazing strategies include year-long continuous, growing season-long continuous, and simple rotational grazing strategies (Roche et al., 2015a). There is limited, if any, use of fertilizers, irrigation, or imported feedstuffs to support livestock herds on these rangelands.

The share of household income derived from on-ranch activities varied substantially across participants. While 34% of interviewees reported they derived the majority (76–100%) of their household income from the ranch, it was far more common for interviewees to have alternative, off-ranch, sources supplementing their household income; 19 and 12% responded they earned 25–50% and 51–75% of their household income from ranch operation activities, respectively. The remaining 35% of producers interviewed indicated they received <24% of their household income from their ranching operations. This is broadly consistent with statistics for the United States; 87% of beef cattle operations made <50% of their income from the enterprise (U. S. Department of Agriculture, 2017). Producers were also asked if they were dependent on the ranch as a source of income and 24% disagreed, 5% were neutral, and 71% agreed.

For 75% of interviewees, alternative sources of revenue were critical to keeping the ranch financially stable. This is consistent with previous research findings that producers often value the "ranching lifestyle" over economic return and profit motives (Gentner and Tanaka, 2002; Roche et al., 2015b). The most cited diversification strategies included converting some rangeland acreage to specialty crops cultivation (e.g., avocados, almonds, walnuts, vegetables, grapes), farming hay, harvesting timber, and facilitating game hunting (i.e., developing hunting clubs or offering guided hunt services).

Threats to Ranches and Rangelands

Among a growing diversity of groups, including livestock producers, environmental organizations, scientists, and public agencies, there is increasing recognition of social, ecological, and economic benefits from the conservation of ranching as a land use. For producers, who typically hold strong and multigenerational connections to the land (Roche et al., 2015b), maintaining and stewarding ranchlands can bring a strong sense of responsibility, as one-fifth generation producer related,

> *"It's a good life. Years ago my daughter said, 'I don't want to be the one that fails at ranching, it's six generations.' That's something there that nobody ever talks about and nobody really wants to think about."* (Interviewee 1)
> *"I've heard a couple of them [his children] say, we don't want to be the one to lose the ranch. We don't want to be the generation that loses the ranch. They [his children] have a strong sense of obligation."* (1)

To better understand current and future challenges faced by producers, we asked, "What do you view as major threats to California's cattle ranches and rangelands?" Transcribed responses to this open-ended question were iteratively reviewed and organized into five main categories, with individual interviewees frequently identifying multiple categories of threats: (i) government regulations and environmental policies (85% of interviewees), (ii) conversion of rangelands to other, higher value land uses (34%), (iii) society's negative perceptions of the beef industry (33%), (iv) climate and resource (e.g., land, water, forage) considerations (28%), and (v) economic considerations and costs of doing business (23%).

Consistent with other studies (e.g., Niles et al., 2013; Roche et al., 2015b), these livestock producers perceive socio-economic factors, in particular government regulations and environmental policies, as major threats to the future of their operations (85% of interviewees). In the category of government, interviewees mentioned regulations (e.g., environmental, transportation, labor) and, specifically, "overregulation" as the most significant threats to their operations. Perceived threats are often rooted in past experiences (Niles et al., 2013), as one producer remarked,

> *"I don't know how you're going to continue to raise cattle with all the environmentalists saying you can't do this, you gotta fence your streams, you can't use herbicides, you can't do that."* (2)

Concerns surrounding environmental policies and agency oversight of privately owned rangelands were tied to the Endangered Species Act (ESA) and species-specific management considerations. The ESA is the primary law in the United States protecting imperiled species from extinction as a "consequence of economic growth and development untempered by adequate concern and conservation" (16 USC sec 1531). The law was written to protect both the species and the habitats upon which they depend. Interviewees expressed concerns about how the ESA has already or would impact their ability to continue to operate in the future. Beyond ESA-listed species (e.g., coho salmon, gray wolf, California condor), producers also expressed concerns about non-ESA listed species that have become highly publicly visible (e.g., wild horses, tule elk, greater sage grouse) and have resulted in diminished producer flexibility and management capacity.

Producers who identified rangeland conversion (34%) as a major threat were particularly worried that residential development and intensive crop production would drive significant losses of open spaces and access to forage. Others have noted the economic marginality of ranching exposes these ecologically diverse landscapes to such conversion and development pressures (Sayre et al., 2013; Cameron et al., 2014). As discussed above, many of the interviewed producers related their operations were under substantial economic stress. For instance, those interviewees who derive limited income from their ranches still consider that income as essential are particularly vulnerable to these pressures. An interviewee who ranches near one of the state's most populous cities expressed,

> *"I guess you call it urban sprawl. More residential development moving into traditional grazing lands. There's going to be a point where some next generation inherits this piece of land and it's going to be just too much to say 'no' to developing it."* (3)

The struggle to remain economically viable was also communicated by producers who cited economic considerations and costs (e.g., insurance, materials, labor, taxes, regulatory compliance) associated with doing business as a threat to their future (23%). These interviewees often reiterated concerns about pressures to convert rangelands to other more profitable uses. These land use changes also impact availability and per acreage costs of privately leased grazing lands, which are a critical forage component for a majority of operations in the state (Roche et al., 2015b). As one producer in the San Joaquin Valley's rich agricultural region commented,

> *"... we are losing more ground to other forms of agriculture than we are to houses. For example, that side of the ranch over there was given to my cousin and I used to lease it from him for my cows. But he has decided to lease it all out to strawberry farmers instead, for a lot more money. I lost that whole side of the ranch.... I lost the whole thing."* (4)

> *"That's what it's coming down to. A lot of these grazing leases, especially in the San Joaquin Valley, those guys are losing ground right and left due to the almonds. You see it up in Sacramento. The irrigated guys are saying, "Hey, let's rip out the irrigated [pasture] and put in trees."* (4)

Producers also discussed inabilities to reach a minimum scale of production efficiency for economic viability due to exorbitant land costs resulting from competition from higher value commodities. One interviewee contended that this cross-commodity competition is a major threat to the sustainability of California's cattle ranches and rangelands,

> *"Right now a big threat is keeping viable when there's a lot of competition for ground. They're planting vineyards like crazy. It's insane. Walnut and almond guys are buying up all the grazing ground. Just finding ground, and enough of it to be an economically viable cattle operation, is a huge challenge."* (5)

When discussing threats to the future of California's cattle ranches and rangelands, one-third of producers also mentioned negative public perceptions of the beef industry. The public dialog on meat production and consumption has intensified in recent years with some arguing meat alternatives and substitutes as the ultimate solution (Laestadius and Caldwell, 2015; Alexander et al., 2017). However, from the landowner viewpoint, rangeland livestock production is the only economically and ecologically sustainable use of these vast landscapes, and without income from traditional livestock market goods they argue these lands would be at great risk for conversion and degradation from more intensive land uses.

Cattle producers also voiced concerns about climate and drought, as well as related issues of forage and water availability. Drought brings substantial and recurrent ecological, economic, and social stresses to California's ranches, which are predominately reliant on rain-fed forages, and has been a formative force for most operations. Ranch management strategies for coping with drought have been adapted over time through multiple generations (Roche, 2016); however, recent extreme events, like the 2012–2016 California drought in which most of the state was under severe conditions, have pushed cattle operations to their limits. Climate and related resource impacts will increasingly challenge ranching operations as rising temperatures, greater precipitation variability, and more frequent and intense droughts are expected to continue (Pathak et al., 2018). Indeed, a majority (82%) of these interviewees have already noted their current strategies would be insufficient in the face of more frequent drought events (Macon et al., 2016). Moreover, recent work has suggested first generation producers are even more vulnerable to increasing climate variability and change due to their smaller networks, lower access to resources, and fewer available adaptation strategies than typical, large, multigenerational enterprises (Munden-Dixon et al., 2019).

Opportunities for Sustainability

We also asked cattle producers "What do you view as the major opportunities for California's ranches and rangelands?" Transcribed responses to this open-ended question were iteratively reviewed and organized into three main categories. Twenty-five percent of interviewees indicated they saw no future opportunities for ranching and rangelands in California. Conversely, 75% of interviewees indicated they did see future opportunities to: (i) improve livestock goods marketing strategies (28% of interviewees); (ii) enhance education and communication to improve consumer perceptions of the beef industry and producers' stewardship of rangelands (33%); (iii) conservation easements (11%); and (iv) PES (11%). An additional 36% of interviewees identified other miscellaneous opportunities (e.g., accessing state and regional park lands for grazing, agro-tourism, mitigation banking). Fundamentally, these producer-identified opportunities generally relate to enhancing integration and connectivity between land stewards and society more broadly, as two interviewees expanded,

> *"I am optimistic. I think there's a lot of opportunities for partnerships,... I believe livestock production is more beneficial than pretty much any other agricultural practice in enhancing soil quality and wildlife. I think there's a lot of common goals for a livestock producer and some of the environmental organizations to put together."* (6)

> *"I do see opportunities. I'm having conversations with conservationists and other people today about the importance of ranching that are better than 15 years ago. I see that as an opportunity. How you actually turn that into something tangible I don't know, but the conversations are happening. Most days I want to believe that public awareness is shifting a little bit too. That's a good thing."* (7)

Producers who discussed improving marketing strategies pointed to opportunities for accessing niche markets and adding value to their cattle via programs focused on consumer values (e.g., organic, animal welfare certified, natural) that also increase livestock-derived revenues. Interviewees often associated "niche marketing" with direct-to-consumer sales or other sales avenues that increased their interaction with consumers (e.g., farmers' markets). Through these streamlined sales channels facilitating direct communication, producers hoped that they would also improve consumers' and society's perspectives on ranching and rangeland stewardship. Niche markets are another avenue through which producers may be compensated for co-production of specific ecosystem services with their traditional livestock products (Goldstein et al., 2011). One interviewee who direct-markets to consumers discussed the messaging benefits of his grass-finished, locally raised beef operation,

> *"So I'm not going to go out and bash conventional business.... But there are some benefits to doing what we're doing and if you want to think about cows grazing in green grass up until their last day of life, I can sell you the beef. The consumer votes with their dollar. They get to choose."* (8)

Direct engagement with, and education of, the general public was also at the forefront of interviewees' minds when they considered future opportunities. This category of responses centered around the notion that if the public learned about the environmental benefits of ranching operations, then they would be more willing and able to internalize the positive externalities and place a value on them (i.e., recognize the ecosystem services they currently receive for free). These producers were optimistic that society would ultimately recognize they are supplying environmental benefits without compensation, and that this would create good will and possibly demand. One interviewee explains,

> *"Niche marketing. That's the whole secret to success. You'd better be innovative. . . . If you could convince all the people who want to buy locally that there's going to be less and less of local products. You have to support your local rancher."* (9)

Eleven percent of interviewees specifically identified conservation easements as an opportunity to enhance sustainability. Thirty percent of all interviewees indicated they already had a conservation easement in place on some or all of their property. Conservation easements are voluntary agreements between a landowner and another entity (e.g., government, and non-governmental organizations) where the landowner agrees to limit the development and/or conversion of land in perpetuity in exchange for a lump sum payment and estate tax benefits. Interviewees viewed conservation easement programs as a means to keep the ranch in their family (e.g., mitigate inheritance tax liability, manage estate planning issues, buy out ownership shares from family members), preserve open space, and maintain habitat for sensitive and endangered species. These one-time cash infusions into ranching enterprises may partially offset the positive externalities generated by these operations while guarding the land against conversion to alternative uses. As one producer in the process of establishing an easement agreement stated,

> *"I'm pretty excited about the fact that we're going to put this ranch in the conservation easement. . . . We don't have any desire to split the ranch up for ranchettes or anything. We want to keep it in the family, want to keep it a viable working cattle operation. That kind of money makes a big difference. It's going to change my life and change everybody's in the family. It's going to change the ranch for generations to come."* (10)

Finally, 11% of producers identified PES programs as potential future opportunities. Many who perceived opportunities in this area specifically mentioned payments for carbon sequestration, habitat for specific wildlife species, and maintaining open space. One interviewee indicated,

> *"The carbon credits and the wildlife enhancement stuff, those things can work right along with our crops and cattle."* (11)

Interest in Ecosystem Service Markets

Ecosystem service markets have been presented as pathways to socially, economically, and ecologically sustainable food systems (**Figure 1C**); however, only 11% of producers interviewed here organically identified PES programs when asked about possible opportunities to enhance sustainability. To elicit a better understanding of producer perspectives, we asked a series of questions about their interest and willingness to participate in ecosystem service-based markets if they existed.

All interviewees were asked if they would be interested in participating in a market in which they would receive payments for producing a specific ecosystem service(s). Nearly 13% indicated they would not consider participating in such a market, 45% were neutral, and 42% stated they would definitely consider participating. Regardless of their initial response, interviewees were asked the open-ended question, "Under what conditions would you be willing to participate in a market for ecosystem services?" Broadly, interviewees stated they would need to have a trust-based relationship with the broker responsible for facilitating market transactions, and that they would be less willing to participate if there was governmental involvement. Many of the producers interviewed expressed specific concerns about broker identity,

> *"My main concern is who is this outfit and what are their ultimate goals? Why are they doing this, and what are they trying to gain?"* (12)

> *"Yes, it [broker identity] makes a difference. I work for the government and I don't trust it. I'm cautious."* (13)
> *"... everything we've ever done on our own properties has always been independent. We have never taken any government money to do any of it. You know there's that little fine print at the bottom of those pages that says, 'We reserve the right to come onto your property to check for wetlands and other stuff.' Have you seen that? Plus, that's right after you give them all your financials in a very large stack. You'd have to give them your whole life right there . . . well, not us."* (4)

Many of the producers interviewed also expressed that their participation would depend on the specific requirements of the agreement, such as duration (Hansen et al., 2018). For example,

> *"I would be very open to something like that. But the problem I have most of the time is, these programs you get involved in, they give you the money up front and it's done. If they had a program whereby it's a yearly source of revenue to pay for sequestration or whatever it is, then you could utilize that revenue on a yearly basis. That lump sum stuff, it always sounds good but you're running less animals and still trying to make a yearly chunk of revenue to make ends meet. The big chunk may last 10-12 years, then it's gone. If you had a revenue source you could depend on that contributed to your annual operating costs, that would be wonderful."* (14)
> *"It might be worthwhile from the standpoint that you'd get paid for doing a lot less work. On the same token, you hear about these places that want to buy your forest service grazing allotment but it's a one-time thing. They're not going to pay you every year...It would have to be annually but also something you could get out of if you wanted to."* (15)

Interviewees also mentioned requirements that would diminish their independence and managerial control of their land and cattle operation would substantially reduce the likelihood of their participation. For example,

> *"I wouldn't want it to become any sort of leverage tool by any agency for them to start dictating management of private land."* (16)

> *"It all depends on how much control they would have over me. I get kind of concerned about that sometimes. That would be a big sticking point."* (17)

Interviewees were asked what ecosystem services they would be willing to sell, assuming a market had developed. The majority of interviewees (78%) did not have specific services in mind. Interviewees were specifically asked if they would be willing to reduce production of livestock goods (and related income) in order to increase overall revenue from the sale of non-bundled ecosystem services. Seventy-six percent of interviewees were positive, indicating maybe (54%) or yes (22%), but raised a list of conditions; interviewees specifically noted they would have to maintain managerial control and flexibility while engaging in these agreements and they would need to know and trust the broker. Twenty-four percent were not willing to trade any livestock-related revenue for revenue derived from non-bundled ecosystem services. Some indicated they are unwilling to trade livestock revenue because they strongly value their roles in the food supply system, and some believe their livestock management does not negatively impact other ecosystem services,

> *"I don't think so. The whole idea of agriculture is to feed the world. So if you cut your numbers in half and every ranch cuts their numbers in half, how do we feed the world?"* (18)

> *"Yeah, if you could tell me that what I'm doing is hurting the environment, but I am not. Why stop what I'm doing? I think the balance is already there. I think we coexist very well. I don't think one* [ecosystem] *service suffers because of the other."* (19)

RECONCILING DEMAND AND SUPPLY FOR NON-BUNDLED ECOSYSTEM SERVICES

Rangeland-based cattle operations are facing substantial financial challenges that potentially threaten their long-term economic sustainability. While society expects the provisioning of non-bundled ecosystem services, the inability to exclude consumption to extract payment means that there is no economic incentive for a market to emerge where suppliers are compensated for their production (Wayburn and Chiono, 2010). Likewise, in cases where such markets are finding limited success, wealth disparity among potential consumers likely create food access challenges and social justice issues. Many economists believe that compulsory mechanisms (e.g., government instituted cap and trade regulations) are necessary to create demand and overcome free-riding of ecosystem services that are public goods (e.g., Jacka et al., 2008). This is why, to date, regulations (e.g., U.S. ESA, Clean Air Act) have been major drivers of environmental markets (Goldstein et al., 2011), while voluntary free-market based environments have languished, relying on consumer preferences and corporate responsibility and reputation to generate demand and value. These regulation-driven markets are not free markets; rather, they require substantial government involvement (a form of market failure), which can vary with shifting political agendas. Those who "demand" credits are compelled by governmental regulation or law to purchase the product to "mitigate" environmental harm they are creating via trade-offs associated with their economic activities. It is not likely that such markets would be broadly welcomed by the cattle ranching community in California and other states (Gosnell et al., 2011)—as willing suppliers—given they are in strong concurrence (85% of interviewees) that government and environmental regulations are actually substantial threats to their own livelihoods. It is ironically wicked that the greatest threat these producers see to their enterprises is the only current means available to create a consumer base for the non-bundled ecosystem services that they do not have private property rights over but society expects them to provision. As one cattle producer summarized after their own investigation of the ecosystem markets available to them:

> *"I just don't know about them, pretty much the only market I found was to governmental agencies, which is not okay with me. They [governmental agencies] create their own rules, force money out of someone else, and then they're out trying to use those folks' money to buy these things from me because of their own rules? They've created their own false economy."* (20)

CONCLUSIONS

The development of markets, and the success or failure of PES more generally, depends upon the political, social, economic, and institutional environments in which they operate (e.g., Muradian et al., 2013). True social, economic, and ecological sustainability on working rangelands will require partnerships between livestock producers and broader society. Unconstrained livestock production systems (**Figure 1A**) and compulsory programs to address trade-offs (**Figure 1B**) are not partnerships, and are not sustainable today or into the future. We assessed the potential for free markets for rangeland ecosystem services to arise as novel opportunities to facilitate partnership and balance ecological trade-offs associated with provisioning livestock goods (**Figure 1C**). We have identified fundamental obstacles on both supply and demand sides that cast considerable doubt on free markets as a panacea for sustainable working rangelands. Such markets will certainly be impracticable in settings such as California where extensive rangelands are at substantial risk of loss to higher value competing land uses, where the very regulations intended to conserve these lands are viewed by livestock producers as the core threat to their livelihoods, and where many producers see no opportunities for enhancing the sustainability of their enterprises (based upon our interviews of 100 ranchers and previous surveys, Roche et al., 2015b). Many rangeland livestock producers face significant socio-economic challenges to maintaining viable operations, and decisions (e.g., regarding rangeland conversion to highest value uses) made under these stressors can place the ecological sustainability of these complex and dynamic ecosystems at risk.

While livestock producers are not motivated by economics alone, there are significant financial impediments to enhancing non-bundled ecosystem services that need to be resolved. This is an essential challenge to developing sustainable food production systems on many of our most threatened rangeland ecosystems. We must solve this challenge together using a diverse set of tools to achieve socially, economically, and ecologically viable outcomes for producers and society. Producers do see opportunities for enhanced sustainability via improved value and marketing of livestock goods that are co-produced with bundled services, participation in conservation easements, and improved connections with society as a whole. These results highlight the continued importance of enhancing existing and new partnerships between producers and society to generate a diversity of strategies to build more equitable food systems and sustain these critical rangeland ecosystems. Examples of successful partnerships to develop strategies to address ecological tradeoffs associated with livestock production can be found across most rangelands systems. The Malpai Borderlands Group in New Mexico and Arizona, USA (Sayre, 2006), the Bi-State Local Area Working Group in western Nevada and eastern California, USA (Duvall et al., 2017), the Thunder Basin Prairie Grasslands Ecosystem Association in Wyoming, USA (Haufler, 2001), the Blackfoot Challenge in Montana, USA (Hittesdorf, 2014), and the Idaho Rangeland Conservation Partnership in Idaho, USA (IRCP, 2020) serve as grass-roots examples of conservation partnerships among diverse stakeholders focused on solutions that address the interdependent social, economic, and ecological aspects of sustainability. Such partnerships employ an array of tools (e.g., incentive programs, in-kind contributions of resources between partners, technical support, research, niche marketing, regulatory relief) to accomplish shared goals (e.g., habitat conservation and restoration, profitable ranching enterprises). Such partnerships require investments by all partners and must be structured around mutual respect and trust, all of which take time, effort, and compromise to achieve and maintain. We suggest these partnerships and others—not false hopes for a rangeland ecosystem service market—are the path forward to sustainably intensify rangeland food production systems while conserving all aspects of these working landscapes and dependent communities.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because they are not publicly available due to confidentiality and consent terms for the study. Requests to access the datasets should be directed to Leslie M. Roche, lmroche@ucdavis.edu.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of California, Davis Institutional Review Board. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

LR and KT conducted interviews. LR, TS, and KT jointly conceived research idea and shared equally in all aspects of manuscript development, drafting, and approved the submitted version.

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frontiers in Sustainable Food Systems

REVIEW
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Grazing in California's Mediterranean Multi-Firescapes

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The California landscape is layered and multifunctional, both historically and spatially. Currently, wildfire size, frequency, and intensity are without precedent, at great cost to human health, property, and lives. We review the contemporary firescape, the indigenous landscape that shaped pre-contact California's vegetation, the post-contact landscape that led us to our current situation, and the re-imagined grazing-scape that offers potential relief. Vegetation has been profoundly altered by the loss of Indigenous management, introduction of non-native species, implantation of inappropriate, militarized, forest management from western Europe, and climate change, creating novel ecosystems almost always more susceptible to wildfire than before. Vegetation flourishes during the mild wet winters of a Mediterranean climate and dries to a crisp in hot, completely dry, summers. Livestock grazing can break up continuous fuels, reduce rangeland fuels annually, and suppress brush encroachment, yet it is not promoted by federal or state forestry and fire-fighting agencies. Agencies, especially when it comes to fire, operate largely under a command and control model, while ranchers are a diverse group not generally subject to agency regulations, with a culture of autonomy in decision-making and a unit of production that is mobile. Concerns about potential loss of control have limited prescribed burning despite landowner and manager enthusiasm. Agriculture and active management in general are much neglected as an approach to developing fire-resistant landscape configurations, yet such interventions are essential. Prescribed burning facilitates grazing; grazing facilitates prescribed burning; both can reduce fuels. Leaving nature "to itself" absent recognizing that California's ecosystems have been irrecoverably altered has become a disaster of enormous proportions. We recommend the development of a database of the effects and uses of prescribed fire and grazing in different vegetation types and regions throughout the state, and suggest linking to existing databases when possible. At present, livestock grazing is California's most widespread vegetation management activity, and if purposefully applied to fuel management has great potential to do more.

Keywords: wildfire, vegetation management, Sierra Nevada, prescribed burning, prescribed grazing, goats, indigenous management

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INTRODUCTION: THE LANDSCAPE OF MARS

On September 9, 2020 we woke up to red skies in our home along the San Francisco Bay. It was more than red skies, actually, the air itself was red (**Figure 1**). Fires a 100 miles away filled the San Francisco Bay basin with smoke—the common comparison was "waking up on Mars." This was unprecedented in our experience. Some smoke in the air over the Bay used to be an occasional

FIGURE 1 | View out the back in El Cerrito, California, September, 2020. Photo: L. Huntsinger.

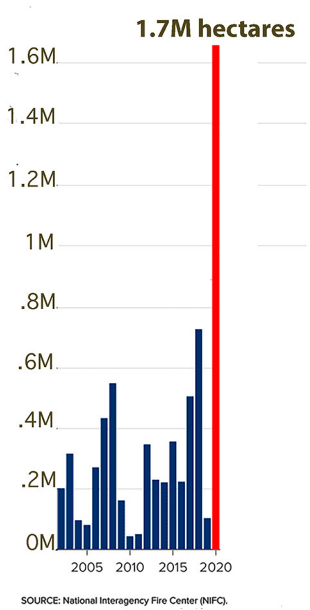

FIGURE 2 | Hectares burned by wildfire in California (National Interagency Fire Center, 2021).

experience, but for the last 10 years California has been pounded with fire after fire. This time it was part of the COVID nightmare of 2020, adding to a year filled with environmental and political dread. More than 1.7 million ha burned that summer and fall, a huge increase over previous years (**Figure 2**). Suppression of people and fire (Davies et al., 2010, 2015), non-native introductions (Germano et al., 2011; Davies and Nafus, 2013), poor land use planning (Radeloff et al., 2018; Kramer et al., 2019), hands off management, and climate change (Pausas and Fernández-Muñoz, 2011; Abatzoglou and Williams, 2016), are all contributors to the wildfire crisis today.

Vegetation and landscape are influenced by the uses made of them and the values and visions of the societies living with them. California's wildfire crisis is partly a function of society's activities at multiple scales: globally, with the economic and political drivers that feed climate change, nationally, with social attitudes, norms, and values and subsequent policies and practices for land management and conservation, particularly as related to science, fire, and traditional knowledge; statewide, in policies for land use and management; county and municipal level, a locus of land use planning and policy; and locally, with the activities of landowners and residents in fire-prone areas. Ecologically, it is a function of a novel climate interacting with a mix of native and abundant non-native vegetation, and the loss of anthropogenic fire regimes that shaped the vegetation for thousands of years. In the Mediterranean climate regions of the state, mild wet winters that stimulate massive vegetation growth are followed each year by 6–8 months of drought at lower elevations. Non-native herbaceous annual species provide millions of metric tons of dried, fine fuels starting in late Spring and lasting until deteriorated by Fall rainfall and replaced with new growth. From year to year, rainfall varies by orders of magnitude, and periods of high rainfall causing floods, and droughts lasting more than a year, are not uncommon (**Figure 3**). This is the perfect set up for regular summer and fall fires.

Livestock grazing in the state converts the non-native annual grasses and forbs on millions of hectares to food and fertilizer, breaking up continuous fuels, removing flammable biomass, and reducing fine fuels that ignite easily and carry fire into woody vegetation. Yet it is startling how few if any of the public agencies in California that manage fire and vegetation, some of the best resourced in the world, mention grazing as a possible fuel management strategy.

The California landscape is layered and multifunctional, both historically and spatially. Managing the firescape is a social-ecological endeavor, and needs to be addressed as such in management and research. Here we look at the contemporary firescape, the indigenous landscape that shaped pre-contact California's vegetation, the post contact novel landscape that led to our current situation, and a re-imagined grazing-scape that offers potential relief. Ultimately, we issue a plea: we need to use all possible fuel reduction techniques to create a more fire-resistant landscape. In addition, there are millions of ha of burnt-over lands in California, and how we manage regrowth, particularly in light of the need for climate change adaptation, is critical. Livestock grazing's management of fire fuels will vary based on wide array of social-ecological factors, including vegetation type, land use, location, and governance, and infrastructure. However, introducing or reintroducing grazing to places where it is needed, and developing grazing strategies that are as effective as possible in reducing fire risk, is much needed.

THE CALIFORNIA FIRESCAPE

The wildfire problem is severe throughout the West and it is becoming more so as climate change warms temperatures

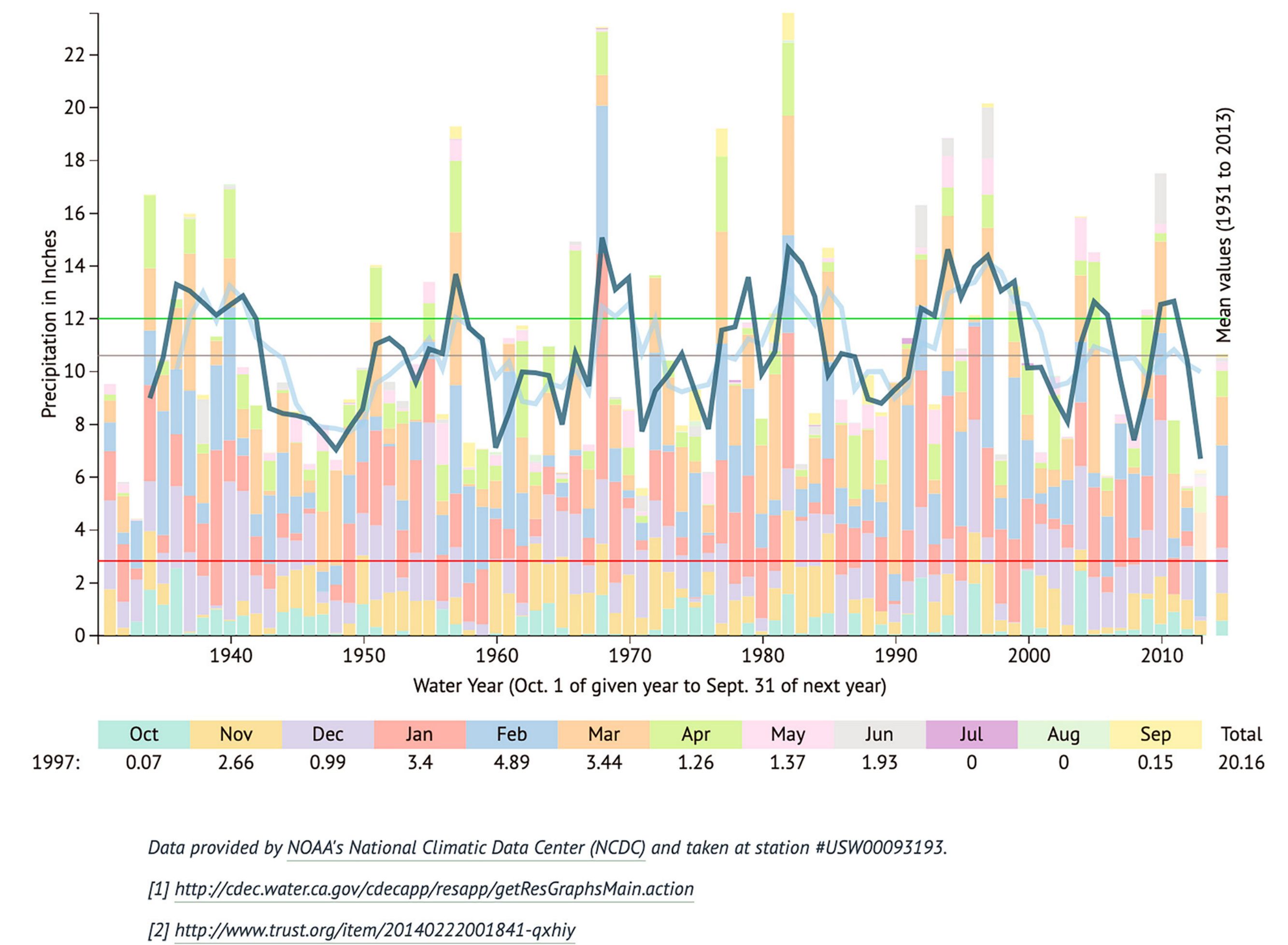

FIGURE 3 | Yearly precipitation segmented by month in Fresno, CA (Polis, 2014, March 7). Red line, total precipitation through Feb. 31 (2.83″); green line, typical rainfall value through Feb; dark blue line, 3 year moving average; light blue line, 5 year moving average. Photo courtesy of C. Polis, Bytemuse.com.

and woody vegetation continues to spread into grasslands, woodlands, and forests (McBride, 1974; Russell and McBride, 2003). California could be called a "perfect storm" when it comes to the wildfire problem: a confluence of climate change and Mediterranean climate weather patterns; massive occupation by high-biomass non-native vegetation; a public that seems increasingly intolerant of active resource management other than protection (Keele and Malmsheimer, 2018); and land use planning that, along with a growing population, has allowed mixing of residential and urban development with natural resource and agricultural land throughout the state (Kocher and Butsic, 2017; Kramer et al., 2019; McBride and Kent, 2019).

Fire suppression has had varied outcomes on plant communities depending on location and vegetation type. For example, in the forests of northern California fire suppression has delayed fire frequencies (Safford and Van de Water, 2014), resulting in millions of dead trees from drought and pests (Goulden and Bales, 2019), and invasion of woody species such as Douglas fir and coyote brush into ungrazed woodlands and grasslands (Lightfoot and Cuthrell, 2015). The resulting fuel characteristics and high fuel loads feed fires of high intensity that are more likely to become crown fires. In the drier southern part of the state, non-native annual plants have invaded formerly sparse shrublands and desert providing fine fuels that carry fire across the landscape. Shrubland areas in the warmer and drier southland are now burning more frequently than under presettlement conditions, and coupled with site occupation by annual invasives, in some vulnerable shrub types, conversion from shrubland to grassland has resulted (Safford and Van de Water, 2014; Allen et al., 2019). Keeley posits that fires in forest ecosystems are driven largely by accumulations of dry fuels, while those in coastal grasslands are in large part driven by winds, though these two factors and many others also have an influence in both types (Keeley and Syphard, 2019). Archibald defines 5 different syndromes of fire regimes, or pyromes, globally based on human impacts and distinctions between crown, litter, and grass-fueled fires (Archibald et al., 2013).

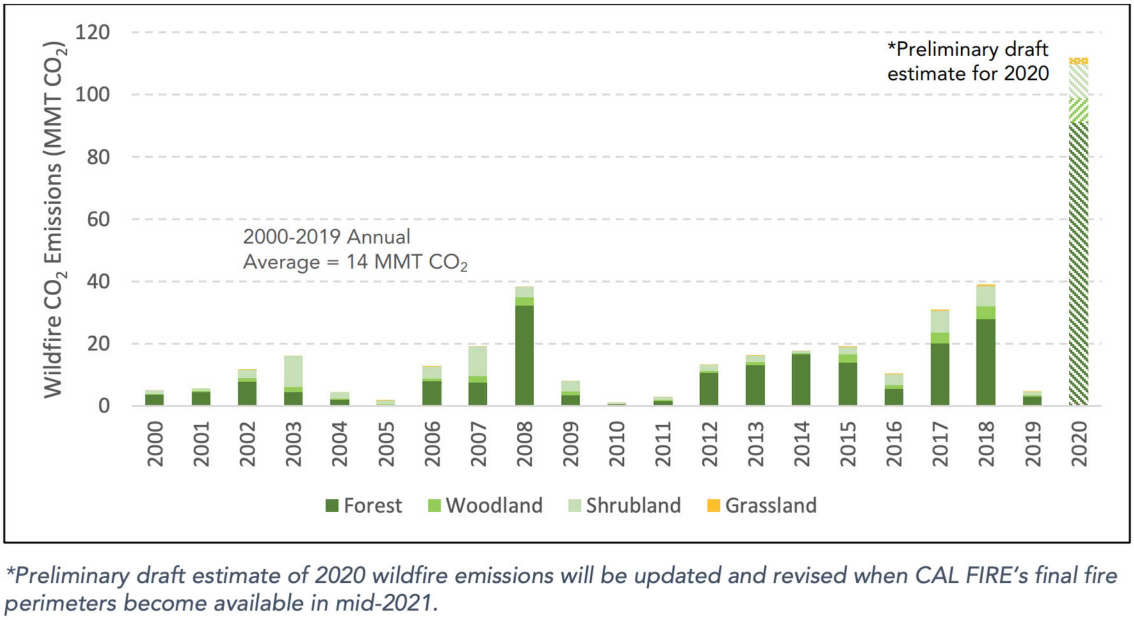

FIGURE 4 | Annual wildfire emissions in California (California Air Resources Board, 2020).

Overall, the state faces deadly wildfires of increasing size, frequency, and intensity, and growing in costs (**Figure 2**). The collateral damage is serious and affects all Californians: smoke threatens human health in the cities as well as near the wildlands (Koman et al., 2019; Liang et al., 2021); carbon emissions and loss of carbon stock contribute to climate change (North and Hurteau, 2011), and costs add to the public ledger (Diaz, 2012; Kousky et al., 2018). For those directly affected by fires, lives and homes are lost, businesses are destroyed, the landscape of home is profoundly changed (Waks et al., 2019). Life is disrupted in terrible ways.

A Deadly and Costly Landscape

Wildfires contribute to climate change by emitting carbon dioxide and black carbon into the atmosphere. According to preliminary figures provided by the California Air Resources Board, in 2020 California wildfires emitted 111.7 million metric tons of carbon dioxide, compared with an estimated 180 million metric tons of carbon dioxide equivalent for transportation in 2018, the most recent year for which greenhouse gas figures are available by sector (**Figure 4**). Globally, from 1997 to 2001, average annual carbon emissions from landscape fires, including wild and prescribed forest fires, tropical deforestation fires, peat fires, agricultural burning, and grass fires, was ∼2 petagrams (2×10^{12} kg) (van der Werf et al., 2010). These emissions affect planetary processes such as radiative forcing, which influences average global temperature, and hydrological cycles, which influence regional cloud formation and rainfall (Yokelson et al., 2007; Cochrane and Laurance, 2008; Fargione et al., 2008; Bowman et al., 2009; Langmann et al., 2009; Tosca et al., 2010). Extensive and intense wildfires in the Pacific Northwest in 2017 injected large quantities into the stratosphere. Solar heating of black carbon caused smoke to rise 12–23 kilometers above within 2 months, where it remained in the stratosphere for more than 8 months (Yu et al., 2019).

Californians from all walks of life, in rural areas and large cities, are being exposed to smoke each summer. The most important risk-related measure of smoke is particulate matter (PM) with an aerodynamic diameter $\leq 2.5\,\mu m$ ($PM_{2.5}$). Wildfire smoke particles impact respiratory health more than fine particles from other sources (Aguilera et al., 2021). Smoke from the combustion of vegetation and buildings is composed of hundreds of chemicals, many of which are known to be harmful to human health (Naeher et al., 2007). In late August and early September of 2020, with hundreds of wildfires occurring simultaneously in the state, Air Quality Index (AQI) data reported by the U.S. Environmental Protection Agency for ozone and PM2.5 in many California counties was often far beyond unhealthy in the later part of August and early September (Burke, 2020).

The massive amounts of smoke released by wildfires is believed not only to cause lung problems (Bassein et al., 2019), but to suppress immune systems—there is evidence from animal studies that the immune suppressive effects may persist for as long as 12 years after exposure (Miller et al., 2020). Air pollution from fires puts exposed children at greater risk of disease in adulthood (Prunicki et al., 2021). Globally, around 339,000 annual deaths were attributed to exposure to landscape fire smoke in a 2012 study (Johnston et al., 2012). Asthma and chronic obstructive pulmonary disease (COPD), were consistently associated with wildfire smoke exposure (Reid et al., 2016). Other potential effects include cardiovascular and mental health (Haikerwal et al., 2015; Wettstein et al., 2018;

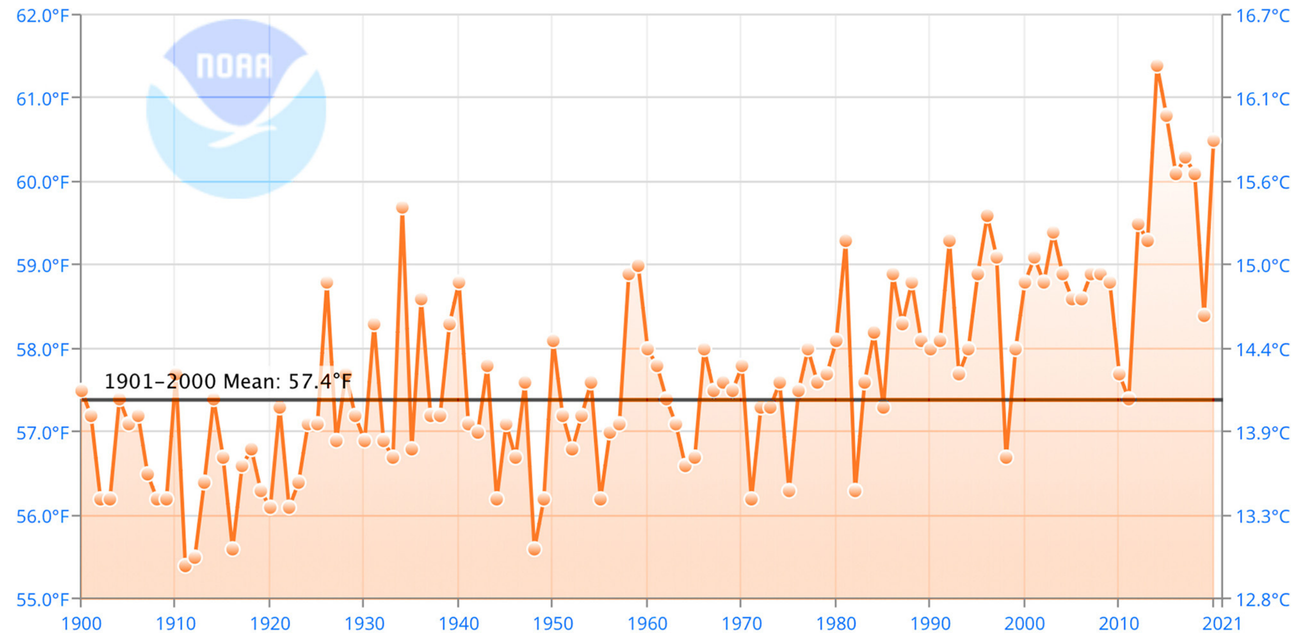

FIGURE 5 | California average annual temperatures, Jan–Dec, 1900–2020 (National Oceanic and Atmospheric Administration, 2021).

Zhang et al., 2018), though inconsistency in findings remains (Moore et al., 2006; DeFlorio-Barker et al., 2019). New research attributes a skin disease to smoke (Fadadu et al., 2021). Common estimates are that thousands of mortalities in California can be related to smoke exposure over the last few years (Burke, 2020).

Costs also come in cold hard cash. California's 2018 wildfires cost the US economy $148.5bn, 0.7% of the country's annual GDP, of which $45.9bn was lost outside the state (Wang et al., 2021). The state itself incurred damages of $102.6bn, roughly 0.5% of the US's annual GDP. While capital losses and health costs within California totaled $59.9bn, indirect losses through economic disruption to 80 industry sectors within the state came to $42.7bn. Productivities were reduced due to illness brought on by fires. The slowdown in production caused ripple effects to economic supply chains within California as in 49 other states, and internationally (Wang et al., 2021). These costs affect all California residents, through taxes, prices, job opportunities, and health costs.

Aside from the Mediterranean climate, and growing populations of people living in homes intermixed with flammable forest and rangelands, there are two lines of thought about the major driver of this current crisis. One is that the main driver is ongoing climate change and its attendant warming, and the other is that the driver is a lack of adequate vegetation management and a history of forest and rangeland use that has left us with an overabundance of flammable vegetation on the land. Both are important, and they are inter-related.

Climate Change and the Firescape

Temperatures in California are warming, exacerbating the influence of drought and changing habitat conditions for animals and plants (**Figure 5**). From 2010 to 2018, nearly 150 million conifers have died of drought and disease in the central Sierra Nevada, at the end of one of the driest series of years on record (Axelson et al., 2019; Larvie et al., 2019). This is a factor in California, but also around the world. In 2017, fires in Portugal took more than 120 lives, in infernos that covered 500,000 hectares (Turco et al., 2019). In 2018, the deadliest fire season in Greek history killed over 100 people (Paphitis and Gatopoulos,

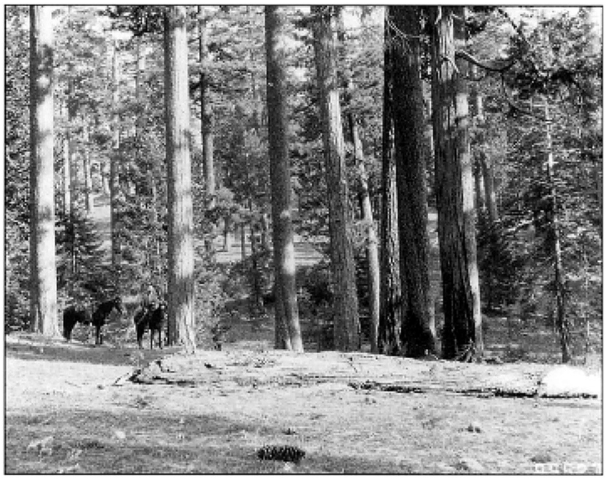

FIGURE 6 | Tahoe National Forest July 1911. Sugar (*Pinus lambertiana*) and ponderosa pine (*Pinus ponderosa*). Note open understory attributed to Indigenous burning and sheep grazing (McKelvey and Weatherspoon, 1992).

2019), and in California, the Camp Fire left 88 people dead and damaged over 18,000 structures (Syifa et al., 2020). Australia's fire-prone savanna and forest caught fire ferociously throughout the country in 2019 during the dry season, the hottest climate year ever (Richards et al., 2020), releasing 337 million tons of CO^2 (Global Fire Data, 2021). Even northern Europe is experiencing a growing fire problem. In 2018 there were more than 50 wildfires in Sweden, including some in the Arctic Circle, and researchers have argued that because of wildfire, plantation forests overall act as a source rather than sink for CO^2 (Naudts et al., 2016).

Studies show that not only is annual mean temperature increasing, but also the seasonal mean temperature and maximum and minimum temperature of seasons are increasing in California (Pathak et al., 2018). These increments in seasonal mean temperature affect the ecosystem differently. Increasing temperatures in winter and spring are generally considered to expedite snowpack melting earlier in the spring and reduce the total amount of snowpack (Westerling and Bryant, 2007). Higher temperatures in summer and fall are usually associated with prolonged drought and higher risk of extreme wildfires. The Sierra Nevada snowpack acts as a reservoir that supplies water to California's vast croplands and cities in the dry season and maintains the health of montane meadows and diverse ecosystems. Because of the rise in temperature, the total volume of snowpack has decreased by 40–90% (Godsey et al., 2013). Higher temperatures and less snowpack have supported forest expansion at higher elevations (Taylor, 1995).

CALIFORNIA'S INDIGENOUS FIRESCAPE

The indigenous firescape was forged by the frequent burning of the state's indigenous people, who arrived at least 12,000 years ago (Lightfoot and Cuthrell, 2015). At the time of contact fire was the major tool Native Americans used for managing the environment they depended on. John Muir's "range of light" (Muir, 1911, p. 316), was a Sierra Nevada of "floods of light" (Muir, 1911, p. 170) with open forests where you could see for miles between the trees. This was a creation of indigenous stewardship (**Figure 6**). Muir took it to be a *wilderness*, and while sensitive to the effects of geology, he seemingly was blind to the landscape engineering of Native Americans, an oversight that unfortunately became an underpinning of the preservationist movement he helped found. Protecting and leaving ecosystems alone would preserve "God's wildness," wherein was "the hope of the world—the great fresh, unblighted, unredeemed wilderness" (Muir, 1979, p. 317). In seeking this imagined wilderness, the creation of a European sensibility and culture that suited the transcendental commitment to the unique values of America, changed ecosystems were created that are now prone to high intensity, seemingly ever-larger and more destructive, wildfires.

California's forest and rangeland management is intertwined with a story of colonial violence, human and cultural suppression, and the focus in this paper, misguided introductions of management paradigms from the more mesic parts of Europe. Estimates of the pre-contact number of indigenous peoples in California are over 300,000 (Cook, 1976), with some estimates much higher (Powers, 1872). Regular burning attracted game and created open grasslands and woodlands where indigenous foods, including acorns and grassland seeds, were abundant. Fire kept less useful conifers at bay (Evett and Cuthrell, 2013). Burning took place often, sometimes annually, and for this reason had not so much fuel to consume, leading to low intensity fires that left few tree scars behind and were limited in extent (Powell, 1890 in Blackburn and Anderson, 1993; Huntsinger and McCaffrey, 1995; DeBuys, 2001; Keeley, 2002; Anderson, 2013). Such fires were reported by early explorers, and described in the accounts of California's indigenous people along with a rich lore on the use of fire for manipulating vegetation. Heady and Zinke (1978) suggest that indigenous people were a major factor in preventing tree regeneration during pre-settlement times.

California's native peoples were much abused by a succession of colonizations by Spain, Mexico, and the United States after 1769. The Spanish rounded them up and forced them to live and work in the missions, Mexico disenfranchised them of the Mission lands they were supposed to inherit, and California enslaved and outright sought to exterminate them. In 1851, Peter Burnett, the state's governor, said that "a war of extermination will continue to be waged between the races, until the Indian race becomes extinct, must be expected. While we cannot anticipate this result but with painful regret, the inevitable destiny of the race is beyond the power or wisdom of man to avert" (Burnett, 1852, p. 15). Close to a million dollars were spent between 1850 and 1852 on "expeditions against the Indians" (Comptroller of the State of California, 1859). Following that, with further attempts to stamp out native culture in the twentieth century, it is no surprise that indigenous long-term knowledge of ecology was not used in developing policies for forest and land management in California. Even the anthropologists who studied California's indigenous people paid scant attention to the use and management of the environment—the prevailing attitude was that they simply lived off nature, rather than actively managing for production of needed materials (Anderson, 2013). This idea contributed to the concept of North America as wilderness and the general discounting by ecologists of former management, and lent justification to the dispossession of native lands (Cronon, 1983). Yet with the technology of fire, Native Californians had a great influence on the California landscape. In interviews, indigenous respondents along the Klamath said, for example, "we burned every year after hunting as we came down out of the forest" (Huntsinger and McCaffrey, 1995).

Early Colonial Impacts on California's Indigenous Firescape

Spanish colonization and other early colonial forays into California left another legacy that began the huge ecological changes that continue today. Inadvertent and purposeful introduction of alien seed into the state in the eighteenth and nineteenth centuries is an ongoing globalization process. The flora has changed, most notably, with a takeover of native grass and forb lands by large-statured annual grasses, pre-adapted to cultivation and grazing, that are able to take maximum advantage of whatever rainfall comes. An annual class experiment in the UC Berkeley greenhouses consistently finds that under identical growing conditions, wild oats (*Avena fatua)*, a typical ubiquitous non-native grass in California, is taller, and has much greater above and below ground biomass, than a typical native bunchgrass, purple needlegrass (*Stipa pulchra)*, after 20 weeks of growth (pers comm. Huntsinger). The non-native grasses produce abundant, highly fecund seed and create a rich, long lasting seedbank; purple needlegrass seed is not as abundant or as likely to germinate (Jackson, 1985). New plants, broadleaves and grasses, continue to arrive, and cannot be eradicated. The subsequent *novel ecosystem* is highly fire prone (Seastedt et al., 2008; Hobbs et al., 2014). Not only do the non-native grasses grow bigger and faster with sufficient rainfall, and crowd and overshadow native species, they are continuous fuels, without gaps between plants, and they die and dry completely in the summer. They choke out habitat for numerous species that evolved without them (Barry and Huntsinger, 2021).

The Spanish introduced livestock grazing to California when they arrived in 1769. Livestock grazing gradually evolved from a "frontier" style of letting animals graze and rounding them up once in a while to more controlled ranch grazing, which grew more established through the nineteenth and early twentieth century (Burcham, 1982). The Gold Rush of 1849 brought graziers into the mountains, creating a system of transhumance from grasslands and oak woodlands to forests and montane meadows (Huntsinger et al., 2010). Private properties in California's lowlands could be quite large, based on Spanish and Mexican land grants that survived statehood, but as the nineteenth century came to a close, the federal government and the state asserted ownership of much of the higher elevation public domain forests, and eventually the deserts, both lands whose physical characteristics limited homesteading. The federal government owns at least 47% percent of California's total area, 19 million ha out of 40 million total (California Department of Forestry and Fire Protection, 2010).

THE TWENTIETH CENTURY FIRESCAPE

The twentieth century California firescape was one of thickening woody vegetation in much of the state, relentless herbaceous annual production and spread, and increased human occupancy and development in forests and rangelands. Concerns about erosion and loss of watersheds due to grazing, burning, mining, and illicit timber harvesting led to the setting aside of *forest reserves* in the Forest Reserve Act of 1891, followed by the 1897 Organic Act that initiated the administration and protection of the reserves as a Forest Reserve System. The Federal Forest Transfer Act of 1905, signed into law by President Theodore Roosevelt, moved control of the forest reserves from Interior to the USDA's Bureau of Forestry, soon renamed the Forest Service, overseeing what would now be called the national forests. The first Chief of the Forest Service and former head of the Division of Forestry was Gifford Pinchot. Pinchot's forest management was shaped by the mentorship of Bernhard Fernow, Chief of the Division of Forestry before Pinchot and formerly a member of the Prussian Forest Service. In general, American foresters took their models for forest management from abroad, including Britain's colonial practices in India. Pinchot studied forestry in western Europe, where he attended L'Ecole Nationale Forestière, the elite French forestry school in Nancy (Barton, 2000). Fernow was from an aristocratic Prussian family, trained in Prussian silviculture. Pinchot became a strong promoter of profitable, *scientific forestry* that provided the "greatest good for the greatest number" by relying on scientific methods (Miller, 2001, p. 330). The early twentieth century was one of much celebrated scientific discovery, and along with that the creation of some of our major land management institutions. Pinchot developed *professional forest management* in the United States, which included a foundational belief that forestry was solely a biological undertaking, based in objective science and immune to the influence of non-biologists (Fairfax and Fortmann, 1990). This fit well with the growing fascination with inventions and science in the early twentieth century.

Forests were promoted as a military and economic good in the Europe of the eighteenth and nineteenth centuries—it took 2000 two-ton oaks to make a British warship (Schama, 1995, p. 173)—and given the frequency of wars and needs for transport, trees were precious and managed intensively. From the first British laws preserving tall timbers in the colonies for ship masts, the management of forests took on a military ambiance. Forests had connections to royalty, with forests set aside as hunting reserves for the King and aristocracy. Growing trees in England became an aristocratic pursuit as their value for the military and national security increased (Schama, 1995). The belief that trees were rare, in need of intensive management, and of high value to society was a politically powerful and somewhat inappropriate ideology used to promote the development of the U.S. Forest Service in a country with vast numbers of trees and a relatively small population (Behan, 1975). In fact, harking back to the military significance of European forests, and reflecting distrust of self-interested local populations, federal and state foresters in California wear paramilitary uniforms. Muir himself commented that "one soldier in the woods, armed with authority and a gun, would be more effective in forest preservation than millions of forbidding notices" for keeping sheepherders out of the Sierra (Bowers et al., 1895). Often Basque, Irish, Italian, or Mexican, sheepherders were lamented as immigrants who did not care for the land, letting their bands of sheep overgraze and damage soils and vegetation. President Theodore Roosevelt wrote the following in 1895:

> *Many of the people in these imperiled legions are not permanent inhabitants at all; they are mere nomads, with no intention of remaining for any great length of time in the locality where they happen to be for the moment, and with still less idea of seeing their children grow up there. They, of course, care nothing whatever for the future of the country; they destroy the trees and render the land barren... The damage from deforestation is often very severely felt in land remote from the deforested region. Because of this fact alone the whole matter should be in the hands of the National Government...and West Point would seem to be the proper place in which to establish the chair of instruction [in forestry]* (Bowers et al., 1895).

Basque sheepherders were characterized "as a group of landless and marginal peasants whose activities were detrimental to the public interest" in the words of a prominent financier in Elko, Nevada in 1909 (Saitua, 2019). Yet in fact, under the Constitution sheepherders had as much right to use the public domain as anyone else.

From Native American homelands the federal government created state-controlled territory open to use by white entrepreneurs and settlers. From the first, the nineteenth century's ubiquitous livestock grazing, immigrant herders, and burning by native peoples and graziers seeking to maintain open landscapes were considered threats to the timber supply and watersheds. Grazing, the primary use of the forests at the time of the initiation of the Forest Service, was initially eliminated, then restored under Pinchot as an important economic activity—actually worth more than forest production at the time. Forest Service policies allowing grazing favored cattle producers over sheepherders, American-born vs. immigrant, wealthy over poor, and Anglo over Hispanic (Sayre, 2018; Saitua, 2019). Grazing was allowed to grow massively during the first World War with the goal of supplying the war effort, but has declined ever since as land management agencies navigate among multiple competing goals for the forests, and seek to balance grazing and forage (Huntsinger et al., 2010). Unfortunately, in the unpredictable and highly varied weather of the West and California, such a balance is elusive and maximizing flexibility is more in line with current understandings of rangeland vegetation—yet the efforts of the agencies have by and large been stability-oriented, relying on set stocking rates. In addition, the *equilibrium* theories that underly the seeking of balance also led to an assumption that reducing grazing would lead to the return of the original state, something that has also proven elusive given all the changes that have occurred in these ecosystems and their natural temporal variability (Keeley et al., 2003; Vetter, 2005; Harris et al., 2006; Seastedt et al., 2008; Hobbs et al., 2014; Allen et al., 2019). Finally, the relationship of grazing with the plants and wildlife that have shared these ranges for decades are not well-understood (Barry and Huntsinger, 2021). What is clear is that suppressing indigenous and agricultural burning, and reducing grazing, facilitated the densification of western forests and, depending on location, brush encroachment into grasslands and woodlands.

Early Explorers and Vegetation Dynamics

Late nineteenth and early twentieth century mountaineers and naturalists observed burning and grazing in Sierran forests and the resulting vegetation dynamics. Clarence King first noted the presence of livestock in the Sierra in 1864 (Gómez-Ibañez, 1977, p. 36). Muir (1911), accompanying a flock of sheep into the Sierra, stated that "almost every leaf that these hoofed locusts can reach within a radius of a mile or two from camp has been devoured." He also commented on indigenous burning to improve hunting grounds. George Sudworth illustrated his report with pictures of the bare forest floor in grazed and burned areas, comparing them to protected areas with lots of understory shrubs and tree regeneration (Sudworth, 1900). He observed several instances of sheepherders setting fires to clear brush to improve the forage supply and make herding easier, noting in one case that 17 fires had been set on the trail of one band of sheep over a distance of 10 miles (p. 556).

Leiberg (1902) attributed the continued existence of "grassy fire glades" to burning and grazing, and noted that when protected from grazing and fire, they rapidly become dense sapling stands. A north coast expedition in 1851 found that such openings in the forests were the only place game could be found for food or their mules could graze—if a glade could not be found the group and the mules went hungry. A group member named George Gibbs wrote that "one of the men in the party and several of the mules starved to death before the trip ended, but the Indians were better acquainted with the location of these oases, as it were, in the midst of desolation, and they maintained regular trails between them." He observed that "[M]ost of these patches if left to themselves would doubtless soon have produced forests, but the Indians were accustomed to burn them annually" (Loud, 1918; Heizer, 1972, p. 230).

William Dudley observed that though most of the pines and firs he saw on his 1895 visit to the Sierra bore fire scars, for some years "no extensive fires had occurred in the region traversed" (Dudley, 1896). Lieberg suspected early miners and indigenous people of having set more past fires, writing that "the aboriginal inhabitants undoubtedly started them at periodic intervals to keep down the young growth and the underbrush. When the miners came, fire followed them" (Leiberg, 1902, p. 40). An analysis of tree ring history in the Sierra conducted in the 1990s led to the conclusion that burning by herders in the 1890s was not necessarily more frequent than that originally carried out by indigenous peoples, but was not as extensive, due to fuel reduction by grazing (Skinner and Chang, 1996, p. 1,058). It seems that in some areas, fire, and grazing were competing for the available fuel. In fact, fire is often part of pastoral and hunting systems around the world because it shifts the vegetation to a state more accessible and more nourishing for ungulate grazers, wild or domestic (Archibald et al., 2012). In both cases, erosion and loss of species can result if the soil is left overly exposed or plants are irreparably damaged. Species and vegetation structure will also likely change with the suppression of either fire or grazing.

Attempts to suppress fire in the early twentieth century led to the first major modern advertising campaign by a government land management agency (Pyne, 1997). During WWI and II preventing fire became conflated with patriotism, with Forest Service posters of Uncle Sam saying "your forests—your fault—your loss" (**Figure 7**). In 1918 the Shasta-Trinity Forest Supervisor sent letters to local stockmen who set fires to clear brush and prevent tree encroachment into meadows, quoting President Wilson as follows: "Preventable fire is more than a private misfortune. It is a public dereliction. At a time like this of emergency and manifest necessity for the conservation of national resources, it is more than ever a matter of deep and pressing consequences that every means should be taken to prevent this evil" (New York Times, 1918). The Forest Supervisor goes on to impute that the fact that WWI was going on made the crime of burning especially heinous. He states that it took the equivalent of 400 men working every day for 4 months to suppress man caused fires, and these men were needed at the front. It was therefore the patriotic duty of the

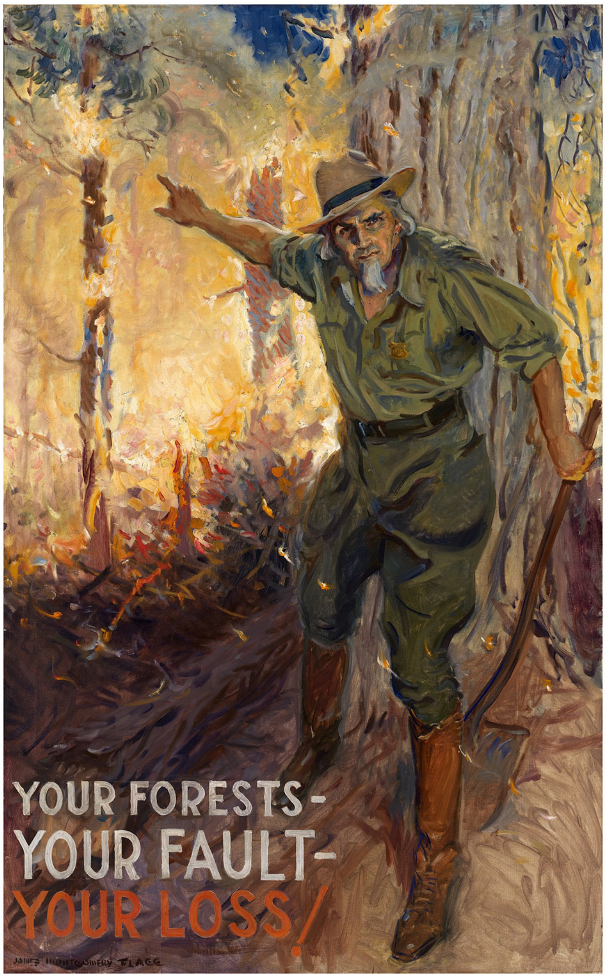

FIGURE 7 | Your forests—your fault—your loss (Flagg, 1934–1943).

stockman to prevent fire (Morrow, 1918; Huntsinger et al., 2010). Eventually, Smokey Bear became the iconic representative of the fire suppression movement. Burning for agriculture and grazing was suppressed, and intentional burning by Native Californians criminalized (Huntsinger and McCaffrey, 1995). On the Shasta-Trinity, once grassy slopes are now covered with brush and dense trees (Taylor, 1995). The outcome now seems inevitable: by mid-May 2021, 10 fires ignited by lightning were already burning on the forest (Dechter, 2021).

California montane forests have undergone great change, with denser trees and more brush in conifer forests and oak woodlands, and federal forests now have higher fire probabilities than forests in other forms of ownership (Starrs et al., 2018). In Northern California Douglas fir (*Pseudotsuga menziesii*) trees are encroaching on oak woodlands (*Quercus* spp. and *Notholithocarpus densiflorus*) in the foothills and lowlands of the state, increasing oak mortality and reducing biodiversity and essential wildlife habitat (Barnhart et al., 1996; Hastings et al., 1996). The buildup of dried fuels in California's Mediterranean ecosystems is one key driver of the wildfire crisis in the state (Starrs et al., 2018; Keeley and Syphard, 2019). Livestock grazing

FIGURE 8 | A long period of drought resulted in millions of standing dead trees in the Sierra National Forest in April 2016. Photo: USFS Region 5.

removes fine fuels like grasses and herbs, and in some ecosystems, can restrict shrub encroachment, particularly if annual grazing is initiated when encroaching shrubs are seedlings that are consumed along with grasses (McBride, 1974; Huntsinger, 1997; Russell and McBride, 2003; Moreira et al., 2020). A recent study found that the main link to climate change as a driver at lower elevations along the coast is the buildup of herbaceous material when rainfall is high (Keeley and Syphard, 2019).

Unfortunately, as scientific forest management developed under Fernow, Pinchot, and their ilk, fire came to be seen as a *disturbance* that prevented the succession of vegetation to the *climax state* of heavy forest, rich with timber (Huntsinger, 2016). Without burning, the dead plant material deposited by grasses, trees, and shrubs—wood, cones, leaves, and needles—piles up beneath the living vegetation. The unpredictable but sometimes severe and multi-year droughts that California experiences lead to tree mortality over-crowded woody vegetation where competition for water occurs. This leads to increasing amounts of fire-feeding dead woody material, and much of it hyper-flammable and well-ventilated standing fuels (**Figure 8**).

Vast areas of California became occupied by brush, dead material, and overly dense trees that are highly vulnerable to drought, making the fire risk even greater. Mountain meadows are being invaded by trees in many areas (Taylor, 1990; Lubetkin et al., 2017). There are several million ha of burned over areas from the fires of the last 5 years with a recovery trajectory that is unknown because it is not clear how climate change will affect regrowth, with the possibility that a long term or permanent brush state will occur in some areas (Davis et al., 2019; Young et al., 2019; Stewart et al., 2020).

THE TWENTY-FIRST CENTURY FIRESCAPE AND REIMAGINING LIVESTOCK GRAZING

Livestock grazing is seldom mentioned in media or policy forums as an important way to reduce fire hazard (Daley, 2021), despite widespread biomass-reduction activities by grazed

TABLE 1 | Definitions of common vegetation treatments in California.

Clearcutting: Cutting of essentially all trees in a location fully exposing the forest floor for the development of a new age class of trees.	
Thinning: Tree removal that reduces tree density and competition between trees in a stand. Thinning serves to concentrate growth and vigor in fewer high-quality trees.	
Harvest: Cutting, felling, and gathering of forest timber, may include clearcutting or thinning.	
Mastication: Vegetation is mechanically "mowed" or "chipped" into small pieces and left on-site reconfiguring a portion of forest biomass from a vertical to horizontal arrangement.	
Other mechanical: A variety of forest and rangeland mechanical activities related to fuels reduction and site preparation including piling of fuels including chaining, lop and scatter, thinning of fuels, Dixie harrow, chaining, etc.	
Prescribed burning: A fire set intentionally for purposes of vegetation management, using a "prescription" of when burning and air quality conditions are appropriate. May be referred to as control burning.	
Cultural burning: Burning practices developed and carried out by indigenous people to enhance the health of the land, including restoration of culturally significant species and landscapes.	
Prescribed/ targeted grazing: Managing and husbanding animals for vegetation management, often goats.	
Commercial grazing: Grazing livestock for production of food and fiber, primarily cattle and sheep.	

domestic livestock, and scattered publications put out by University of California Cooperative Extension (Nader et al., 2007; Rao, 2020; University of California Cooperative Extension (1), 2021; University of California Cooperative Extension (2), 2021; University of California Cooperative Extension, California Invasive Plant Council, Environmental Protection Agency, 2021). New state initiatives to manage fuels include relaxing environmental rules to allow for fuel breaks and prescribed fire, but the role of livestock grazing is usually overlooked. For example, California's Wildfire and Forest Resilience Action Plan, produced in January 2021, includes a large picture of cattle grazing under electrical lines like those responsible for major ignitions, a setting where the removal of biomass by grazing is clearly valuable. While mentioning healthy grasslands and advocating for prescribed burning of them, the report never mentions grazing at all (Forest Management Task Force, 2021). California has extensive lands with flammable fire-adapted vegetation: 82% of the state is undeveloped including ∼20 m ha of government and 13 m ha of private land (California Department of Forestry and Fire Protection, 2010). The wildfire crisis apparent calls for the use of every mitigation and prevention tool we have (**Table 1**), except for the most widespread fuel removal activity in the state.

Each year grazing cattle are estimated to remove at least 5.3 billion kg of biomass (drywt) from close to the 8 million ha of private California rangelands with available data. On average, that is about 1,500 kg per ha (Rao, 2020). Amounts of biomass produced and consumed vary by orders of magnitude annually and by region, as do recommended grazing levels (Becchetti et al., 2016). Fire hazard reduction is a side benefit of production of meat and milk—grazing reimagined as purposeful for removing fuel and altering vegetation structure could emphasize fire-prone locations or vegetation types, targeting areas as needed with more intensive removal (Nader et al., 2007), and combining grazing with burning and clearing. In addition to grazing for livestock production by cows, sheep, and goats, businesses providing grazing services for fire hazard reduction are emerging and flourishing. Some land trusts, parks, and preserves use commercial livestock grazing and/or targeted grazing services to reduce biomass for fire as well as to enhance biodiversity. For example, the East Bay Regional Parks in the San Francisco region (East Bay Regional Parks, 2021). The California Department of Fish and Wildlife provides *Excess Vegetation Disposal Permits* for commercial livestock grazing to make the purpose of grazing leases clear to the public.

Grazing as a fire-fighting tool faces further challenges in addition to neglect by agencies with vegetation management responsibilities. California range livestock numbers have declined since the 1970s. While 70% of livestock forage is provided by California's mostly private annual rangelands (Huntsinger and Bartolome, 2014), public lands, more than 50% of the land area of the state, also support livestock grazing, especially in summer when high elevation meadows provide rich feed while the grasslands below are dry. While many parks, conservation properties, and reserves use grazing to enhance biodiversity and reduce fire risk, and for a notable number of endangered species grazing is a useful habitat treatment (Barry and Huntsinger, 2021), increasingly conservative stocking rates and exclusion of stock are common on public land that is managed by federal and state agencies. Federal public lands throughout the western United States have experienced a dramatic decrease in livestock numbers during the past two decades. Ostensibly to meet agency conservation objectives, California's public lands managed by the Forest Service (USFS) and the Bureau of Land Management (BLM) have seen a 36% decline in grazing, measured in *animal units* on the land per month (AUMs) (**Figure 9**; Oles et al., 2017), just at the time it is needed.

On some state and park lands, after over a century of grazing, livestock were excluded to meet expectations of wilderness, increase naturalness (Fried and Huntsinger, 1998), or reduce perceived conflicts with wildlife (Barry and Huntsinger, 2021). In other areas landscape fragmentation has made grazing difficult to manage and more costly. Among private landowners, on both rangelands and forest there are an increasing number who are not production or management oriented, preferring to leave the land as "natural" as possible. A significant number of owners have the stated main ownership purpose of land speculation, a number that appears to be growing (Ferranto et al., 2011).

In addition to a fuel and climate problem, intermixing of housing and development with forests and rangelands in California and throughout the West increases risks to property, lives, and human health (Radeloff et al., 2018; Kramer et al., 2019). An estimated one-third of homes in the US are built in or near wildland vegetation and constitute the *Wildland Urban Interface* (WUI) (Kramer et al., 2019). In California, 75% of buildings destroyed by wildfire were in a WUI (Kramer et al., 2019). Thus far, land use planning processes have

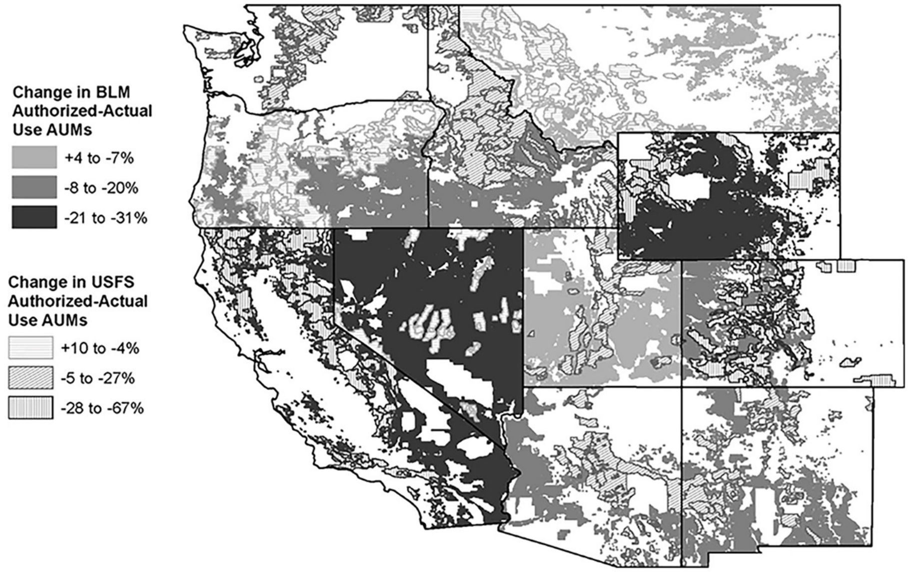

FIGURE 9 | Change in animal unit months (AUM) on public lands in 11 states in the western U.S. between 2000 and 2015. The *lightest color* represents slight positive to slight negative changes in AUMs. *Darker colors* represent increasingly negative changes in AUMs. *Solid polygons* represent lands administered by the Bureau of Land Management (BLM). *Hatched polygons* represent lands administered by the U.S. Forest Service (USFS). Data were sourced from BLM and USFS annual reports (Oles et al., 2017).

FIGURE 10 | In understory burning, one goal is to prevent harm to the larger trees, while suppressing growth of shade tolerant conifers that would crowd the stand, and create openings diverse species. In a cultural burn, goals may include enhancing culturally significant species and landscapes, and in some cases, influencing plant growth form for weaving or carving. The understory here contains a high density of beargrass (*Xerophyllum tenax*), a valued basketry resource requiring fire to promote desired leaf growth (Photo: Frank Lake, US Forest Service).

been inadequate to prevent the creation and expansion of the WUI. Promotion of *defensible space*, clearing around homes, and *hardening* of homes against ignition are strategies widely promoted to homeowners, and can reduce home loss, as can adequate roads for fire-fighting access and other factors. Recently, California fires have burnt through WUIs and into neighboring communities, using houses as a source of well-dried fuels, and leveling blocks of homes and shopping centers (Kramer et al., 2019).

California's fire problems are not unique. Traditional agricultural systems offer some insights into how grazing might be used. *Land abandonment* is a frequent topic in Europe's Mediterranean regions, and wildfire is a common and much feared consequence (Collins et al., 2013; Moreira et al., 2020) as farmers and graziers leave. Grazing and agriculture are often unabashedly considered key to reducing fire hazard in southern Europe (Lovreglio et al., 2014; Colantoni et al., 2020; Damianidis et al., 2020; Moreira et al., 2020; https://www.mosaicoextremadura.es/en/home-en/). Spain and Portugal offer an example of the use of grazing and tree management in to create a fire-resistant landscape. In the southern Iberian Peninsula, grazing is part of traditional agricultural systems with a histories of more than a 1000 years, such as the Spanish *dehesa* and Portuguese *montado* (Bugalho et al., 2011). Featuring oaks that are pruned to have no low branches, well-spaced trees without continuous crown fuels, and an understory of annual grasses (many common in California), they are generally heavily grazed by combinations of sheep, goats, cattle, and pigs, as well as wild grazers like red deer. Every 10 years or so, unpalatable brush is cleared or the understory is cultivated with a grain crop. The result is one of Spain's most fire resistant landscapes (Ortega et al., 2012). Removal of grazing or cessation of understory clearing has been found to increase fire hazard and reduce biodiversity (Joffre et al., 1999; Tarrega et al., 2009). For many communities, forms of agro-sylvo-pastoralism are a key strategy used to create *productive firebreaks*. On the other hand, the vast eucalyptus and pine forest plantations common to Portugal and Spain, growing at high density and with continuous fuels, are among the most likely vegetation to burn and have fueled recent catastrophic fires (Fernandes et al., 2016).

Fire Hazard Reduction Efforts and Reimagining Livestock Grazing

At the present time in California, in the media and popular outlets the emphasis is on prescribed burning, promoted as a natural part of the ecosystem (**Table 1**). An answer to our fire problem, in these terms, is to restore frequent fire to the ecosystem, substituting for the indigenous and natural burning that once reduced brush and thinned trees, creating more open grassland and forest. The United States Forest Service, the National Park Service, *CalFire* (the state fire and resource management agency), landowner groups, and Native Californians have embraced prescribed burning, intentional or allowed burning for management purposes that takes place within a *prescription* that includes a number of variables including weather and environmental characteristics. Cultural burning, burning practices developed by indigenous people to enhance the health of the land, including restoration of culturally significant species, also seems to be increasing in agency and public acceptability (Sommer, 2020; Lake, 2021; Marks-Block et al., 2021; **Figure 10**). Invasion of conifers and shrubs into grasslands burned regularly under indigenous management means that restoration of burning practices is key to restoring traditional landscapes and ecosystems (Keeley, 2002; Evett and Cuthrell, 2013). In the last decade indigenous groups have actively sought access to land and restoration of indigenous management practices, with cultural burning a common goal, augmented with hand clearing when required to restore conditions for safe burning (Sommer, 2020).

The argument is made that prescribed burning is the natural way to remove fuels and restore a more fire-resilient landscape, but this debatable. The climate is warming, highly flammable non-native annual grasses are common, there is fuel

TABLE 2 | Comparison of fuel reduction treatment alternatives in California.

Treatment	Application	Cost	Benefits	Constraint[a]	Products	Extent (est)
Manual	Clear or prune herbaceous and woody plants	\$1,980/ha[b]	Low impact, targeted. Steep slopes.	High cost, small areas. Fuel may be left on site or need disposal.	No	Minimal
Mastication	Chop and grind surface and ladder fuels by machine.	\$250–2,500/ha[c]	Targeted, masticated areas can be more safely burned to remove fuel	Fuel left on site but converted to horizontal structure	No	Minimal
Mechanical thinning or harvest	Tree removal, reducing density, or cutting for timber	\$90–2,500/ha[b] Some costs may be offset by timber sales	Costs offsets from timber. Only method to remove established trees (besides wildfire)	Soil disturbance Can meet fuels reduction targets. Accompany with burning or mastication to reduce surface fuels.	Wood products, saw logs, chips	±1 million ha/year[e]
Prescribed fire	Reduce ground and surface fuel, including dead wood, invasives.	Variable Cost \$7–2,700/ha[d]	Lower cost at scale. Benefits fire-adapted plants. Selective of fuels by intensity.	Smoke, regulations, site conditions, air quality, liability, risk—especially with ladder fuels. Selective by fuel quality.	No	±45,000 ha/year[f] (increasing)
Prescribed/ Targeted grazing	Reduce ground and surface fuels, control invasive species	Variable Cost \$1,090–2,700/ha[e]	Low risk, few regulations. Selective by species and intensity. Different livestock for different goals.	Higher cost, small areas. Fences, water, maybe herder needed. Prune up to 4–6 feet off the ground. Large woody vegetation not removed, desired plants may be.	Often a specialized service rather than for producing meat or milk. Often goats	31,000 ± ha/year[g]
Commercial grazing	Annual herbaceous biomass removed. Trampling and grazing may impede shrub spread or regrowth.	\$0 to revenue; cost-sharing, reduced rent for infrastructure help, complex plans.	Lowest cost if infrastructure present. Annual treatments easy. Low risk. Brush seedlings may be removed /suppressed, annual grasses eagerly consumed.	Requires fences and water. Forage must meet livestock needs or supplement is needed. Mature woody vegetation not removed. May consume desired plants. Limited by livestock production needs, bottom line.	Food and animal products	16 million ± ha/year

Please note that local assessment is needed to determine how each technique works on a given site.
[a] *All treatments produce greenhouse gas emissions, all may enhance biodiversity or meet other resource management objectives.*
[b] *Lasaux and Kocher (2006); http://cecentralsierra.ucanr.edu/files/88262.pdf.*
[c] *United States Department of Agriculture (2005).*
[d] *Quinn-Davison and Stackhouse (2019).*
[e] *Macon (2014).*
[f] *California Air Resources Board (2021).*
[g] *Roger Ingram (pers. comm.) UCCE emeritus, August 6, 2021).*

accumulation and vegetation change in many areas, and housing is mixed with forests, woodlands, and shrublands (Yoon et al., 2015). To reduce the risk, burning when fuels are not at their driest, often outside of the natural fire season, is common. Burning out of season affects plants and animals in different ways than burning within the fire season they have evolved with. Cultural burning is also difficult to conduct within the traditional season because of ecosystem change and risk to buildings and infrastructure, making compromise part of the picture. Yet deliberate burning is needed to develop a more fire resistant landscape. Further, cultural burning offers indigenous knowledge to inform burning efforts, and is a heritage activity that cannot only address wildfire risk, but contribute to the revitalization of indigenous cultures.

Around 45,000 ha of California vegetation was burned deliberately in 2019, a considerable increase from the <16,000 ha burned each year since 2007, but only about 0.14% of the 33 m ha of wildland in California, and 3% of the nearly 1.7 million ha burned in the 2020 wildfires (**Table 2**). About 37% of the 2019 burned area was in forests, the rest on rangelands (California Department of Forestry and Fire Protection, 2010; California Air Resources Board, 2020). Land management agencies and private rangeland and forest landowners are eager to do more. Landowner-driven *prescribed burning associations* are being reinstated and resuming higher levels of activity (Hagarty, 2020, October 19). The state fire agency is working to streamline the permit process for such burns. But prescribed burning can be costly, with extensive planning, insurance, and monitoring needed. Multiple regulations from more than one agency, as with fire agencies and air quality entities, slow the process. The need to burn under ideal weather, fuel, and air quality conditions makes the window for burning small, resulting in delays. Fears of liability hamper private landowners. The permitting agencies have also not been overly receptive to prescribed burning not implemented by them (Hagarty, 2020, October 19; Susan Kocher (pers. comm.) UCCE, August 6, 2021.) and yet funding has been tight for agency-conducted vegetation management activities. The premier fire-fighting and forestry licensing agency, the California Department of Forestry and Fire Protection or CalFire, is typical—spending on prevention lags far behind spending on suppression because it is easier to get funding to fight fires than to prevent them (**Figure 11**). And, often the places that need burning the most are the most dangerous to burn (Wood, 2020). Getting prescribed burns done on schedule can be cumbersome. It requires a smoke management plan to be filed with the local air quality district and mandates a burn plan be filed with the corresponding fire agency. Considering that burned areas need to be reburned eventually to maintain the effects of burning, with all the barriers and the cost, there is a possibility that instead a burn will prove to be a one-time treatment with limited duration of effect (Fernandes and Botelho, 2003).

Other vegetation management strategies should be promoted as much as prescribed and cultural burning, including grazing. They include burning, clearing, and grazing (**Table 2**). The federal government, for example, working with the state, has introduced a forest thinning program with the goal of scaling up thinning and clearing to ∼400 t ha of forest per year, about 0.03% of California's forestland, by 2025 using brush clearing, logging, and prescribed fires (United States Forest Service and State of California, 2020). California has budgeted $1 billion for 2020–2021 to increase prescribed fire on state owned lands and develop a network of fire breaks (Forest Management Task Force, 2021).

Fires, aside from lightning strikes directly to trees, generally start in fine, dry fuels, where they spread swiftly. Early in the season, grasslands, and shrublands dry first, becoming fuel for some of the state's most destructive wildfires (Weill, 2018). Grasses are 1 h *fuels*, drying in 1 h of hot and dry weather, while trees are 100–1,000 h fuels (Sikkink et al., 2009). Grasses are standing dry material, with plenty of oxygen mixed with dried fuel. Fine fuels from dry herbaceous vegetation and the small plant materials that fall to the forest floor act as kindling, leading

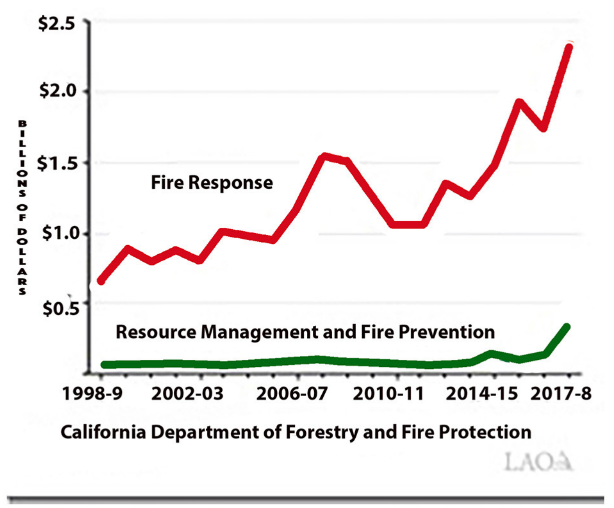

FIGURE 11 | Spending on fighting fire vs. preventing fire, CalFire (Legislative Analyst's Office, 2018).

FIGURE 12 | Targeted grazing for fuels reduction using sheep in a suburban park in San Jose, California. Photo: S. Barry.

to the burning of larger and larger fuels until the fire can burn huge trees. Changing continuous to discontinuous fuels is crucial (Weatherspoon and Skinner, 1996). Tree canopy is fine fuel too, so creating breaks in the canopy and breaks that reduce the ability of ground fires to reach the canopy are important fire prevention and fighting strategies (Nunamaker et al., 2007). Unfortunately, the aggressive, invasive non-native annuals that now dominate most California grasslands are continuous fuel that allow fires to spread across the landscape. They invade shrublands and burned or cleared forest areas, including fuel breaks (Keeley et al., 2003; Merriam et al., 2006).

Reimagining Grazing

Commercial livestock grazing is the predominant land use and the most widespread vegetation management activity in California, occurring on about 12 million hectares of public and private lands. Livestock producers have strong interest in integrating grazing and prescribed burning for vegetation management, reducing shrub encroachment, and improving forage, as well as reducing fire hazard (Hagarty, 2020, October 19; California Cattlemen's Association, 2021). Another advantage of using commercial grazing is that it is relatively inexpensive because the owner is making an income from the enterprise. Production-oriented grazers can charge less or even pay for decent forage when infrastructure like fences and water points are adequate. At the same time, livestock producers must match livestock needs with forage quality and availability, infrastructure, and animal handling practices. Planning complex grazing treatments, or grazing at high intensity, will sometimes incur costs and reduce income. Subsequently, grazing for fire prevention may come at a cost, though likely lower than any other technique we are aware of.

There have been attempts to evaluate the role of commercial livestock grazing in reducing fire hazard (Launchbaugh et al., 2008), but to date studies have focused on lands grazed primarily for production purposes, limiting options for management. For example, one researcher lamented that the ranchers providing cattle to graze his sites for research into beneficial grazing effects on wildlife habitat would simply not graze hard enough because they feared weight loss in the cattle (Germano et al., 2011). In California, livestock grazing tends to be light to moderate to maintain a herd size that be healthy through periodic drought. Regardless of fire risk, the grazing in an even a highly fire-prone area may not be intense enough to always make the optimum impact. Traditional practices will need to be re-thought when emphasis shifts to fire hazard management. For example, many ranchers whose animals graze wetter or higher elevation rangelands in the summer have historically tried to leave forage behind for the return of the herd in Fall. The dry forage supports cattle before unpredictable fall germinating rains facilitate new forage growth (Barry, 2021), but this practice, unfortunately, leaves standing dry biomass on the ground. As a solution, left behind forage could be broken into discontinuous units separated by areas fully grazed before the livestock leave. Another option is supplementation instead of dry forage in the fall—again an increased cost that could be compensated for active fuel reduction. In short, be most effectively used for fire hazard reduction, grazing will need to be planned for purposefully controlling fuels, and some practices will need to be incentivized because of higher costs to the producer.

Goat and sheep grazing companies are popping up all over the state offering targeted or prescribed grazing for specific purposes (**Table 2**). The use of small ruminants for targeted grazing for fuels management tends to be more acceptable to the public. The public see a mob of goats or sheep crowded in a small area munching on vegetation and recognize the activity as a service (**Figure 12**). They do not find goats or sheep intimidating, and may be unaware that such animals may eventually be slaughtered. Many targeted grazers do not participate in meat or milk production and do not obtain income from marketing animal products, so putting weight on the animals is not a priority, allowing greater flexibility in grazing intensity. In addition, managing certain fuels may best be accomplished with a class of animals like older wethers (castrated male goats or sheep) that have little value for livestock production.

Grazing for fuels management in California is often associated with such small ruminant prescribed herbivory or targeted grazing, which is conducted as a service for a per acre cost. The cost is relatively high compared to commercial grazing, but not hand clearing, which may be the only other option. Grazing infrastructure such as fencing is often not available and the targeted grazer must provide temporary fencing and livestock water. Depending on the setting, animals generally need a herder to ward off dogs and predators, and to maintain temporary fences that are irregularly breached. Sometimes the vegetation to be controlled is not of adequate quality to support the livestock, and supplemental feed is required.

Different Animals and Different Regions

The characteristics of the animals and of the ecosystem affect what can be done and how it should be done with grazing. Knowledge of dietary preference and grazing patterns is key to developing grazing plans for fire hazard reduction and biodiversity enhancement. Different breeds and species may consume different things and forage differently; animal experience with particular ecosystems may also be a factor. Goats prefer brush and tolerate secondary plant compounds better, sheep prefer more broadleaves, and cows are basically grass vacuum cleaners. Goats and sheep are excellent for steep or rocky slopes, smaller areas around homes and development, and brush control. Extensive grasslands are ideal for cattle, as it can be not only less costly, but they are easier to fence in, not as susceptible to predators, and one cow consumes as much as 5 goats. Grazing different kinds of livestock together might be applied in some situations.

The various approaches each have their benefits and can be combined in innovative ways. While herbicide and hand treatments leave dead, flammable plant material *in situ*, grazing animals consume the material and process it at the site, converting it into food and fertilizer. If trees are palatable, livestock may browse the lower branches, breaking up fuel ladders that might carry fuel into the canopy. Annuals and some shrubs return with the winter's rainfall, but commercial

TABLE 3 | Examples of fire and grazing relationships in 4 shrub types in four regions of California [General references: Sampson and Jespersen (1963), United States Department of Agriculture (2021)].

Brush type	Location	Target species	Fire dynamics	Grazing management	Conservation value	Hazard	Grazing references
Coastal montane chaparral (Chamise, *Adenostoma fasciculatum*; Manzanita, *Arctostaphylos* spp.; Scrub oak, Quercus dumosa)	Coastal ranges	Chamise, *Adenostoma fasciculatum*	Fire intensity, time and interval control species composition and diversity. Dense stands require prefire treatment to reduce fuels for safety. Early spring burning can promote vigorous resprouting. Small fires, frequently spread may reduce large catastrophic wildfire events. Herbaceous annuals and perennials germinate post-fire. Erosion may be an issue on steep slopes.	Grazing not effective in dense mature stands. Young chamise readily consumed by goats—in one case chamise made up 70% of the goat diet (Sidahmed et al., 1978). Goats can retard regrowth post-fire and support maintenance of fuel breaks. Greater livestock utilization of Adenostoma is supported with supplementation. Animals lose condition on chaparral alone. Grazing sprouts intensively after fire can cause significant shrub mortality; young growth is preferred, spring grazing often recommended.	High conservation value with diversity of age class and species. Low conservation value within dense stands	Decadent stands are highly flammable. High intensity fire from crown fires are typical. Fire impacts include smoke and post-fire debris flow.	Sidahmed et al., 1978, 1982; Green et al., 1979; Barro and Conard, 1991 Minnich and Franco-Vizcaíno, 2003; Narvaez et al., 2011; Moreno and Oechel, 1991
Interior chaparral (Chamise, *Adenostoma fasciculatum*; *Manzanita* spp., *Arctostaphylos* spp.; Ceanothus)	Ring around central valley occurs with oak woodland						
Coastal transition	Coastal grasslands, central to northern California. Re-colonizer in coastal sage scrub and chaparral post-fire.	Coyote brush, *Baccharis pilularis*	Baccharis increases in absence of fire and grazing.	Baccharis increases in absence of grazing. Grazing and trampling limit invasion or regrowth in grassland	Supports coastal scrub reestablishment. Invades high quality habitats like coastal prairie.	Increased fire hazard, more intense fire with shrub encroachment	Biswell et al., 1952; McBride and Heady, 1968 (https://www.fs.fed.us/database/feis/plants/shrub/bacpil/all.html)
Soft chaparral (coastal sage scrub, *Artemisia californica*)	Southern California coastal terraces, plains, and foothills	Annual grasses, exotics	Fire adapted, 30–150 year return interval but suppression and fine fuels (annual grasses) result in large fires, too frequently <20 years. Fire not followed by grazing slows regeneration to shrubs.	May be managed to benefit threatened shrubs by removing flammable annual grasses, as shrubs are not highly palatable, but more study needed. Timing of treatment seems to matter, with grazing concentrated during green grass growth period. Unmanaged browsing (sheep and goats) detrimental.	High conservation value supporting numerous endemic species	Brush does not accumulate high fuel loads, non-native annual biomass increases fire risk	Bradbury, 1978; Conlisk et al., 2016; Allen et al., 2019

(Continued)

TABLE 3 | Continued

Brush type	Location	Target species	Fire dynamics	Grazing management	Conservation value	Hazard	Grazing references
Sierran mixed conifer	Central Sierra Nevada, mid elevations	Deerbrush, *Ceanothus integerrimus*	Deerbrush (*Ceanothus integerrimus*) resprouts and regrows vigorously after fire, can get tall enough to carry fire into the canopy. Regular burning post-clearing suppresses shrubs. Shade may eventually exclude shrubs as forest matures, most common in openings, meadows, along roads and waterways.	Cattle, sheep, and goats find deerbrush highly palatable. Mature shrubs are not suppressed as tops are out of reach and the shrub is a vigorous resprouter and tall, but younger shrubs can be suppressed through grazing. Post fire or clearing shrubs can be excluded if grazed the first season and annually. Typically present manzanita (*Arctostaphylos* spp.) and gooseberry (*Ribes* spp.) are less palatable.	Fixes nitrogen, important wildlife browse. May retard conifer regeneration post-clearing.	Shrubs can get tall, creating ladder fuels. Forests are overly dense in many areas, prone to drought mortality, large fires have occurred in this type in recent decade.	Kosco and Bartolome, 1983; Huntsinger, 1997

In all cases the other species present need to be assessed and considered, and soils protected from erosion.

grazing can predictably be applied every year, extending the effects of more sporadic treatments (Fernandes and Botelho, 2003). It also makes it safer for future prescribed burning. Regrowing plants and shrubs are highly nutritious and often, though not always, suppressible by livestock (Huntsinger, 1997). By reducing the ratio of woody to non-woody vegetation components, the landscape becomes literally more palatable for livestock and wildlife. Prescribed burning and grazing do share some limitations: mature woody overgrowth is not so feasible for removal by prescribed burning or grazing, and mechanical or manual treatments often have to be applied first.

Different regions and vegetation types have different vegetation dynamics, and different potential for grazing and fire management, calling for different approaches. Effectiveness and practicality vary by location, vegetation type, animal type, and even the characteristics and experience of individual animals and breeds. In a given year, weather may shape outcomes, as will the timing, intensity, and duration of grazing treatments. Availability of different kinds of animals and experienced producers also varies by location. Much needed information is clearly lacking, but in fact the risks of using grazing are low, and grazing practices are easily adapted as needed.

The applicability of various practices will vary with species, vegetation type, and location (**Table 3**). Ultimately grazing management should be adaptive, and outcomes monitored, as existing information is limited. Talking to local livestock managers, Extension agents, NRCS, and service grazers is an excellent way to start. Various publications provide further guidance on grazing management and illustrate the variation among regions and ecosystems (Nader et al., 2007; Ingram et al., 2013; Lovreglio et al., 2014; Spiegal et al., 2016; University of California Cooperative Extension, California Invasive Plant Council, Environmental Protection Agency, 2021).

CONCLUSIONS

While professional foresters and agency land managers once considered intentional burning a hostile act and damaging to forests, and livestock grazing a danger to ecosystems, there is considerable evidence that with good management, neither of these things is true. Thanks to the efforts of many and a lot of research, prescribed and cultural burning are gaining in acceptance, even to the point where is has been stated that the agencies will encourage landowners and others to conduct burns with training and permits. The same cannot be said about livestock grazing, yet it needs to be.

California faces a massive fire problem, and our most active fuel managers should not be left in the barn. California's current firescape is increasingly a result of land abandonment, with vegetation and landscapes tended by Native Californians for thousands of years left largely to fend for themselves in the twentieth century. Now more than ever highly fire-prone land is left unstewarded. Removal of grazing from lands grazed for 200 years leads to vegetation change that may not only support fire, but degrade habitat for an array of species. Terming a

FIGURE 13 | Cattle grazing the Dublin Hills Regional Park, Alameda County, California remove significant fine fuel from the landscape. Once livestock are removed, as in many places in the world, land abandonment has allowed fuels to grow abundantly, leaving highly ignitable, standing dry grass through the summer and fire season. Photo: S. Barry.

continent a wilderness was indeed a late nineteenth century misnomer built on colonial ideologies, unknowingly carried into the twentieth century embedded in preservation initiatives, and still very much a factor today. Yet there is no reason to believe that hands-off management or protecting ecosystems will result in any recognizable recovery. Without restoration of previous ecosystems as a reasonable target, innovation in the face of novel ecosystems and climate is needed (Hobbs et al., 2014).

Forest management practices imported from western Europe emphasized harvesting and planting trees for sustainable timber production, but ignored the role of fire, treating it instead as a disturbance that interferes with an orderly process of vegetation development (Huntsinger, 2016). Efforts to preserve and protect forests run aground on the need for indigenous practices and cultures that created them, and until now, public forests in particular seemed abandoned when it comes to the human and fire role. Those living in proximity to National Forests and overgrown public lands can be fearful of vegetation conditions that seem to be deteriorating into a major fire hazard, while at the same time, they feel powerless to do anything about it. Native Californians are actively pursuing opportunities to restore traditional management practices to the land, but with the changing climate and huge areas that have shifted to unprecedented vegetation conditions, all tools must be brought to bear.

Some public attitudes challenge effective fuel management. While prescribed burning is widely promoted by various agencies, and in the media, grazing is not. Grazing for commercial livestock production is an extensive land use that has low energy requirements and relies mostly on rainfall-based forage on lands unsuitable for crop production. Grazing has significant biodiversity benefits through removing non-native, habitat-choking biomass (Huntsinger and Oviedo, 2014), and produces unprocessed, high quality, food. The public often does not recognize how much of California's landscape is grazed because grazing is extensive and livestock may not be often be visually present. They often do not make the connection with much appreciated wildflower blooms facilitated by removal of exotic biomass. When they encounter cattle on public lands people may be intimidated by their size and unfamiliar with cattle behaviors (Barry, 2014). Negative and often exaggerated media claims about the contribution of cattle to climate change and environmental degradation raises questions about why cattle are allowed to graze, especially on public open space lands meant to preserve nature. Yet all of agriculture, including livestock production and its attendant activities, emits around 8% of California greenhouse emissions, while transportation emits 41% (California Air Resources Board, 2021). Emissions from rangeland grazing are mostly in the form of short-lived gases that do not accumulate over long periods rather than carbon dioxide that persists and accumulates for hundreds of years in the atmosphere, and the land conserved through ranch ownership is a carbon sink.

Grazing seems harder for professional forestry and land management agencies to accept as a fuel reduction tool. For the forestry and fire agencies, who, especially when it comes to fire, operate largely under a command and control model, ranching and ranchers are a diverse group not generally subject to agency regulations. In a culture of uniforms, regulation, and careful control, grazing is managed by all sorts of people with all sorts of goals, at all kinds of scales and on private lands, without permits from a regulatory agency, lacking a set of common and licensed plans and practices. While forest landowners must get a permit from CalFire and several other agencies to sell timber, rangeland landowners are not required to get agency approval to sell livestock into the production chain. The somewhat chaotic characteristics of the ranching industry, and the high value placed on individual autonomy, seem likely to be challenging to a command and control agency. This has also limited prescribed burning.

The current discussion of foodscapes and sustainable food production offers an opportunity to work toward changing some attitudes, and ideally, marketing could be linked to creating sustainable and fire-resistant ecosystems. Grazing around the WUI can reduce flammable fuels and create productive, or *working fuelbreaks* (**Figure 13**). If you talk to fire-fighters on the ground, grazed areas make valuable staging areas for fire-fighting (Huntsinger, pers. com.). Agencies should widely promote grazing in outreach material about wildfire. CalFire and the Forest Service have, after all, responsibilities for rangelands as well as forests.

In addition to more information about the effectiveness of deliberate grazing for fire control, knowledge of what ecosystems, regions, and vegetation types are amenable to different treatments, including grazing, is essential for practitioners. As with any treatment, knowing the very local vegetation conditions and dynamics is needed (Fernandes and Botelho, 2003). A statewide database of what is known about best practices for using fire and grazing in different parts of the state should be part of the developing effort to reduce catastrophic fire. Existing databases, in particular the Ecological Site Descriptions of the United States Department of Agriculture Natural Resources Conservation Service (NRCS) should incorporate fire hazard reduction goals. Ecological Site Descriptions should be finished for California. The state and transition models used are ideal for incorporating and organizing data-driven vegetation management information and results from research and other verified sources. Incentives could provide compensation to commercial grazers if biomass removal has to go beyond what is best for production. Management innovations and incentives for purposeful grazing to reduce fuels are likely still to result in less expensive control than with prescribed burning and many other treatments, and the need for planning and management is no more and maybe less onerous. Integrated planning using fire, thinning, and grazing offers the potential for long lasting effectiveness.

Learning from and working with Natural Resources Conservation Service and University of California Extension personnel with expertise in grazing management and experience working with livestock producers could be a step forward. In fact, there is an unfortunate gap between forestry and rangeland management as professions, yet the vegetation does not recognize this gap, intermixing and sharing resources across the landscape. Livestock grazing, prescribed and cultural burning, and thinning and clearing are essential tools as California faces climate change and landscape fragmentation. Each have a significant part to play as we work to restore fire resistant landscapes. People in general don't like to see familiar landscapes change (Waks et al., 2019), but regardless, our forest and rangeland landscapes are already changing. The question we have to answer is, do we want to give ourselves choices about how future places look and what they provide, or let it be decided for us?.

AUTHOR CONTRIBUTIONS

LH wrote the draft manuscript. SB contributed writing and ideas and edited it. Both authors contributed to the article and approved the submitted version.

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Livestock Mobility Through Integrated Beef Production-Scapes Supports Rangeland Livestock Production and Conservation

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Much of the world's rangelands contribute to food production through extensive grazing systems. In these systems, livestock producers, pastoralists, and ranchers move grazing animals to access variable feed and water resources to create value while supporting numerous other ecosystem services. Loss of mobility due to political, social, ecological, and economic factors is documented throughout the world and poses a substantial risk to rangeland livestock production and conservation of rangeland resources. The integration of production-scapes can facilitate livestock mobility through transportation and trade. This paper describes the beef cattle production system in California, where transporting and marketing animals integrate an extensive grazing system with intensive production systems, including feeding operations. Analysis of livestock inspection data quantifies the magnitude of livestock movements in the state and the scope of production-system integration. Over 500,000 head—47 percent of the state's calf crop—leave California rangelands and are moved to new pastures or feedyards seasonally over a 12 week period each year. Most ranchers in California, from small-scale producers (1 to 50 head) to larger producers (more than 5,000), participate in the integrated beef production system. Less than 1% of steers and heifers go from rangeland to meat processing. Like pastoralists, ranchers strategically move cattle around (and off) rangeland to optimize production within a variable climate. Ranchers indicate that their movements result from changes in forage quality and quantity and support their desire to manage for conservation objectives, including reducing fire fuels, controlling weeds, and managing for wildlife habitat. Inspection data, as well as direct observation, interviews, and surveys within the San Francisco Bay area, reveal the extent to which the region's ranchers rely on saleyards to facilitate the movement of cattle and integration of production systems. Saleyards and cattle buyers drive beef production efficiency by sorting, pricing, and moving cattle and matching them to feed resources in more intensive production systems. However, transactions lack traceability to inform policy and consumer choice. New data technologies like blockchain can provide traceability through integrated production-scapes and facilitate market development to support grazing landscapes and consumer choice.

Keywords: pastoralism, grazing, blockchain, ecosystem services, conservation, ranching, beef production, feedyards

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INTRODUCTION

Grazed lands occupy about 60 percent of the world's agricultural land and substantially contribute to communities' social, economic, and environmental well-being ([FAO] Commission of the European Communities Food Agriculture Organization of the United Nations, 1997; [FAO] Food Agriculture Organization, 2018). For millennia, the sustainable management of grazed lands has depended on pastoralists moving their animals to access enough high-quality feed to create value. Mobility allows grazing animals to opportunistically utilize highly variable plant and water resources over both time and space in response to stochastic events (Niamir-Fuller, 1999). Livestock mobility is critical for livestock production and resource conservation on grazed lands.

Most of the world's grazed lands, 91 percent, can be described as rangelands (Reid et al., 2008). These are lands on which the potential natural or native vegetation is predominately grasses, grass-like plants, forbs, or shrubs. They are often characterized as marginal and managed with little to no agronomic inputs and are generally unsuitable for crop production (Follett and Reed, 2010; [FAOSTAT] Food Agriculture, 2016; Mottet et al., 2017). Grazing by herbivores under the stewardship of pastoralists and ranchers is the primary production system on the world's rangelands, allowing these lands to contribute to the production of food and fiber (Behnke, 1994; Brunson and Huntsinger, 2008; Reid et al., 2008; Davies et al., 2010, 2013; [FAO] Food Agriculture Organization, 2018).

In addition to providing food and fiber, rangelands provide a myriad of other ecosystem services, including supporting biodiversity, capturing and storing water, sequestering carbon, and providing for recreation (Sala and Paruelo, 1997; Davies and Hatfield, 2007); and there are growing expectations that these services will be protected and conserved (Blench, 2001; Barry et al., 2007; Brunson and Huntsinger, 2008). This paper considers how expanding the beef cattle production-scape supports livestock mobility as well as rangeland livestock production and conservation. Through a case study, I demonstrate that ranchers use transportation, trade, and markets to expand their production system boundaries and facilitate the mobility of their livestock so as to manage and benefit from the variability of California's rangelands despite the loss of more traditional or more independent forms of mobility.

The degree of mobility and, consequently, land tenure has been used to define pastoralism types, e.g., nomad, semi-nomad, transhumant, and differentiate them from livestock ranching (Ingold, 1980; Ruthenberg et al., 1980). Whereas, pastoralists and their livestock are mobile and rely on communal lands, ranchers are considered to be stationary and to hold exclusive rights to property. In reality, a clear distinction between pastoralists and ranchers is difficult to draw. While ranchers, at least in the western United States, generally do not either stay or move with their livestock, they will herd animals to move them away from an area or to a new pasture, often on horseback or with dogs (Derose et al., 2020), and transhumant is also a practice (Huntsinger et al., 2010). Similarly, ranchers may not graze communal land, but they also do not always have exclusive land rights. For example, in California, ranchers may own their land, but many access a mix of private and public rangelands through grazing leases (Liffmann et al., 2000; Lubell et al., 2013), which they rely on to sustain their ranching operations (Sulak and Huntsinger, 2007). Grazing rights may be exclusive on leased land, but the ranchers' tenure of this land is often insecure and shared with other uses, including recreation, hunting, and wildlife conservation (Huntsinger et al., 2010; Wolf et al., 2017).

The difference between pastoralism and ranching are best understood along a continuum. However, it is the attributes that pastoralism and ranching share that are critical to understanding extensive livestock production and differentiate it from other agricultural production systems. Ranching and pastoralism are conducted in a non-equilibrium ecosystem–arid and semi-arid rangeland—characterized by the natural growth of herbaceous vegetation, which tends to be highly responsive to weather and relatively unresponsive to grazing (Behnke et al., 1993; Jackson and Bartolome, 2002). Ranchers and pastoralists use livestock mobility and their knowledge of the highly variable ecosystem and the livestock's nutritional needs to support livestock production, rangeland health, and lifestyle (Huntsinger et al., 2010).

Globally, livestock mobility, and pastoralists and ranchers' ability to manage rangelands and sustain their livelihoods are at risk. Pastoralists and ranchers require grazing lands that are extensive and diverse for rangeland livestock production, but access to grazing land is in many places eliminated or restricted. From Africa's drylands to China's grasslands, and to the United States' western rangelands, grazing lands are being taken over by other land uses or set aside for conservation (Yeh, 2005; IIED and SOS Sahel, 2009; Cameron et al., 2014). Growing populations and economics drive subdivision and land-use change, but the widespread misunderstanding of use and management of rangeland resources also lead to loss of use (ACC [African Conservation Centre- US] Maasi-Malpai, 2006; Huntsinger et al., 2010).

Pastoralists have historically been construed as culprits in desertification narratives that blamed them for overgrazing (Swift, 1996; Behnke and Mortimore, 2016; Davis, 2016). Similarly, rangeland degradation in the western United States has been attributed to ranchers and their management of livestock grazing (Huntsinger et al., 2012). While newer paradigms have developed from understanding arid and semi-arid lands as non-equilibrium and valuing local ecological knowledge, these paradigms have yet to fully inform policy or prevent barriers to pastoral and rancher management of rangeland (Krätli, 2016; Wolf et al., 2017). The new pastoral paradigm acknowledges that pastoralists use livestock mobility to strategically manage and benefit from variable rangeland resources and, thus, manage grazing impacts and avoid degradation within a variable climate (Roe et al., 1998; Niamir-Fuller, 1999; Krätli and Schareika, 2010). In non-equilibrium ecosystems, abiotic factors, primarily precipitation, are more significant in determining vegetation structure, function, and dynamics than grazing or other ecological processes (Westoby et al., 1989; Behnke and Abel, 1996). This explanation does not negate the fact that grazing impacts vegetation, but it recognizes that grazing's impact is a function of climate variability.

While the current movement around ranching, "working landscapes," does not call out the role of livestock mobility, it more broadly recognizes that ranchers can manage livestock production to be compatible with the conservation of rangeland resources (Plieninger et al., 2012). However, there remains a need to fully understand the production systems that support livestock mobility and working landscapes, especially as the systems have become more complex, and system boundaries are expanded. In recognition of ecosystem services associated with rangeland livestock production that are not currently valued in trade or marketing, and maybe even obscured in the expanded production-scape, I also consider opportunities afforded by new technology (e.g., blockchain) to communicate values to buyers and consumers.

MATERIALS AND METHODS

Study Area

Cattle grazing is the most extensive land use in California. Nearly 26 million ha of California (62 percent) are classified as rangeland ([CDFF] California Department of Forestry Fire Protection, 2003), with about 12.8 million ha grazed by domestic livestock—mostly beef cattle ([CDFF] California Department of Forestry Fire Protection, 2017). The California Department of Forestry and Fire Protection (2017) defines rangelands as lands on which existing natural vegetation is suitable for grazing domestic livestock for at least part of the year. Like most of the world's rangelands, these are marginal lands that would require substantial interventions to support other agricultural uses. Rainfall is highly variable, with a coefficient of variation >30 percent for most California, suggesting non-equilibrium conditions (Ellis and Swift, 1988; Dettinger et al., 2011). The predominant types of rangeland in California include Mediterranean rangelands, cold desert steppe, and warm desert (Huntsinger and Bartolome, 2014; George et al., 2015) (**Figure 1**).

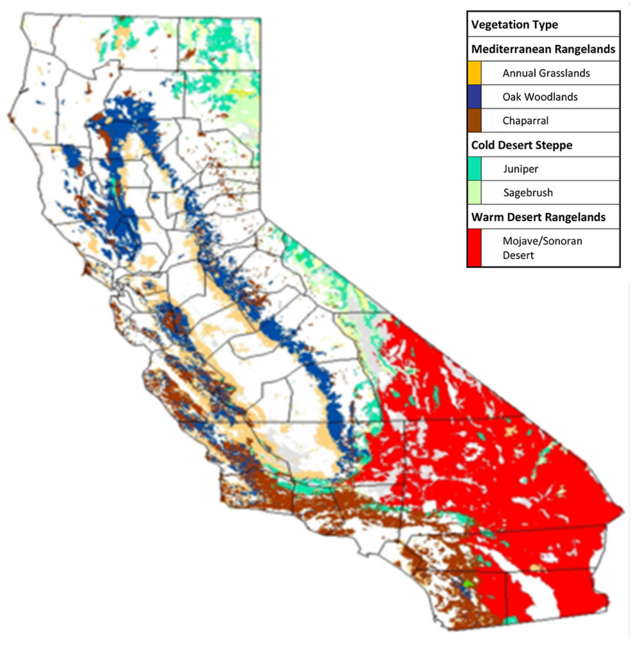

FIGURE 1 | Location of major California rangeland vegetation types (adopted from George et al., 2015). Lands colored white are non-range landcover types (e.g., forest, urban, more intensive agriculture).

Although California's Mediterranean annual rangelands are just over one-third of the state's rangelands (**Figure 1**), they support most of the state's beef cattle grazing, providing at least 70–80 percent of the forage in the state (Huntsinger and Bartolome, 2014; Salls et al., 2018). More than 80 percent of these rangelands are privately-owned ([CDFF] California Department of Forestry Fire Protection, 2017). Ranging from sea level to an elevation of about 2,000 m, a long, hot, dry season of 6–9 months is complemented by a wet, cool winter growing season. Many annual rangelands are grazed year-round—with only breeding animals, primarily cows, being left on rangeland through the dry season when feed quality is inadequate for a growing animal.

The Mediterranean annual rangelands are characterized by the dominance of non-native annual grasses in open grasslands and understories. They include about 10 million ha of grassland, 2 million ha of oak woodland and savannah, and nearly 3 million ha of chaparral and coastal scrub ([CDFF] California Department of Forestry Fire Protection, 1988, 2003). Common grassland and understory plant species include Eurasian annual grasses (e.g., *Bromus, Avena*, and *Festuca* spp.), with a few native perennial grasses (e.g., *Stipa*, *Poa,* and *Elymus* spp.) and a great variety of forbs. Intermixed are more than 66,000 ha of valley-foothill riparian and other moister habitats that may have a higher component of perennial species ([CDFF] California Department of Forestry Fire Protection, 1988, 2003). These rangelands, part of the California floristic province, are recognized as a global hotspot of plant biodiversity (Heady, 1995; Myers et al., 2000; Huntsinger and Bartolome, 2014).

The cold desert steppe is mostly above 1,158 m elevation and includes 2 million ha of sagebrush grasslands and pinyon-juniper woodlands that are more than three fourths federally owned. Grazing on privately-owned lands is supported by transhumance. Livestock graze montane meadows in the summer, which are managed by the US Department of Agriculture, United States Forest Service (USFS), and then graze lower elevation land in the winter, which is managed by the US Department of the Interior, Bureau of Land Management (BLM) (Huntsinger and Bartolome, 2014).

Over 9 million ha of arid lands, California's warm desert is primarily owned by the federal government and managed by the BLM. Low elevations, low rainfall, and warmer temperatures year-round are characteristic. With low resistance and resilience to anthropogenic disturbances (Milchunas, 2006; Belnap et al., 2016), these lands are considered marginal for livestock production. Nevertheless, livestock may graze for 7 months from spring to fall, utilizing pulses of forage that follow sporadic rainfall, especially in higher elevations, where perennial grasses are more abundant (Huntsinger and Bartolome, 2014).

As described for the different types of rangeland in California and similar to other pastoral livestock production systems globally, livestock movements on California's rangelands occur at different scales depending on the spatial and temporal variability of the resources and other aspects of the production system (Adriansen, 1999). California ranchers generally keep stock densities low (e.g., > one animal unit per four to 16 hectares) and use large pastures (e.g., 50 to 1,000+ ha), allowing livestock to graze selectively. Especially in larger fields, cattle may be periodically herded, and cows or experienced animals may be kept to guide young or naïve animals (Vallentine, 2001, p. 206; Launchbaugh and Howery, 2005; Derose et al., 2020).

Grazing of domestic livestock has been a widespread use of land throughout most of California for around 200 years (Burcham, 1981). Beef cow numbers representing the cowherd and the primary type of livestock grazing on California's grazing lands peaked in 1982 at nearly 1.2 million head (Saitone, 2018) and today average about 730,000 beef cows and replacement heifers ([USDA] United States Department of Agriculture, 2017). There are also small numbers of 307,000 ewes and 100,000 non-dairy goats (Huntsinger and Bartolome, 2014).

Within California, the San Francisco Bay Area was selected as the study area to evaluate the driving factors and infrastructure facilitating cattle movement. Despite its notoriety as a hub for high-tech industries, the region's most common land use is cattle grazing (Huntsinger et al., 2016). Ranchers use older traditions, including moving and gathering cattle on horseback, and ecological knowledge to manage cattle grazing over 700,000 ha, 39 percent of the region's private and public lands, including regional parks, habitat conservation lands, and watersheds (Huntsinger et al., 2016). Cattle grazing on the region's annual rangeland promotes species diversity, including the conservation of several threatened and endangered species (Bartolome et al., 2014; Barry et al., 2015).

Livestock carrying capacity on California rangelands varies both seasonally and annually but expressed on a yearly basis ranges from 4 to 12 ha/animal unit/year. In addition to seasonal differences, carrying capacity and stocking rates vary by climate (annual precipitation and temperature) and site conditions such as soil and vegetation health, plant residues, topography, tree cover, water availability, and the presence of noxious weeds (Barry et al., 2016). These factors interact to influence plant growth and the length of the growing season. Livestock management, including movements and resulting rangeland health, is also a significant influence on carrying capacity (Krueger et al., 2002).

Study Methods

I used a mixed-methods approach to understand how cattle movements and production are influenced by market integration. Through data analysis, interviews, and surveys, I studied movement patterns and factors driving individual ranchers to move cattle from grazing land. I identified the infrastructure needed to support livestock movements and the information provided with livestock transactions through data analysis and direct observation of livestock sales.

Cattle Movement Data Analysis

To assess cattle movements, I used data collected by California's brand inspectors. Brand inspectors check brands on livestock when they are transported as required by state law. They also check any documents, such as shipping manifests and bills of sale, that show ownership when livestock is sold and record the description and number of animals shipped. I analyzed movement data collected in 2017 and 2018 at the following times ([CDFA] California Department of Food Agriculture, 2020):

1. At the time of sale or transfer of ownership
2. Prior to moving out of state
3. Prior to slaughter
4. Upon entry to registered feedyard
5. Prior to release from a saleyard

Since the California Hide and Brand Law was approved in 1917, cattle have been inspected to protect owners from loss of animals by theft, stray, or misappropriation ([CDFA] California Department of Food Agriculture, 2020). According to the California Bureau of Livestock Identification, 50 brand inspectors inspect 3.2 million head of cattle a year. Inspections occur in every county in the state except San Francisco, at ∼20,000 ranch locations, 30 livestock saleyards, 31 feedyards, and four major meat processing plants. Cattle owners entirely finance the brand inspection system through brand registration and fees for the inspection service.

There is no current mandate to individually identify an animal in the US, so state brand inspectors identify cattle as individuals or in lots. They use descriptions based on the owners' hot iron brand, if available, breed or color, and class of animal (e.g., cow, bull, heifer, steer, calf). Brand inspectors also record the date of inspection and change in status, location of inspection, the reason for inspection, cattle county of origin, and owner identification. If applicable, inspectors will include information on the cattle buyer and destination and the agent who facilitated the sale.

In California, brand inspection data includes movements of cattle used for dairy, beef, breeding stock, show, and rodeo.

TABLE 1 | Beef cattle production in California and the San Francisco Bay region, grazing land resources, and producer numbers.

	California	Bay Area[a]
Rangeland (ha)[b,d]	12,800,000	183,000
Irrigated pasture (ha)[c,d]	196,000	2,400
% Total grazing land irrigated (ha)	1.5%	1.4%
Number of beef producers[e]	10,254	458
Number of beef cows[e]	682,372	33,073
% producers with 50 head or less	78%	62%
% of total cattle for area[e]	14%	9%
Average herd size (head)	66	72

[a]*Includes Alameda, Contra Costa, Santa Clara, and San Mateo Counties.*
[b]*State data from CDFF 2017.*
[c]*State data from USDA NASS 2017.*
[d]*Regional data from County Crop Reports (Alameda, Contra Costa, Santa Clara, and San Mateo 2017).*
[e]*USDA NASS 2017.*

I categorized cattle as beef or dairy using breed and color information. Cattle of beef breeds were classified as dairy if they originated from a dairy. Dairy cattle in California are primarily raised in confined feeding operations or, if pasture-based, they are raised on improved pastures. Few cattle for dairy production utilize dryland pasture or rangeland. Dairy cattle contribute a significant number of steers and heifers, and cows to beef production. These numbers are presented in the results for comparison (**Table 2**).

Movements of beef cattle from grazing lands to new pasture, animal feeding operations or feedyards, saleyards, or meat processing plants were identified based on inspection type, buyer, and destination information. Cattle movements associated with shows, breeding, or rodeo were excluded based on sale type, event or destination, or buyer. Buyer and destination information was not generally available for cattle sold at saleyards. If beef producers retained ownership through processing, cattle were considered as direct marketed. Data were categorized by the producer's size based on the number of head inspected by premise (owner) identification.

Saleyard Direct Observation and Interviews

I directly observed cattle buyers and sales at seven "feeder" (animals ready to be put on feed after reaching an appropriate size on forages) sales conducted at three different saleyards in California from May to July 2019. Feeder sales are held as special sale events to attract buyers and local cattle sellers during the time described by one of the saleyards as their "busy off-the-grass season." I reviewed the written, oral, and visual information presented to buyers for each sale transaction. Written information was provided in a sales catalog by one saleyard for three observed sales, but each saleyard provided information onscreen. Sales lasted 8 h or more, and around 5,000 head of cattle sold in 300–400 separate lots moved through the sale ring.

I recorded information in an electronic survey during each sale, for 679 lots of 1 to 45 head of cattle from the San Francisco Bay Area. I noted in the survey information announced and actions taken to influence price and marketability by either sale yard staff or buyers. Actions included sorting animals based on size or type. In some cases, buyers requested additional information, such as the geographical origin of the cattle. For example, in one case, a potential buyer wanted to know the distance of the cattle's origin from the coast. The auctioneer called the cattle rancher during the auction to verify. To fully describe the type of information available to livestock buyers and attributes associated with beef cattle production from the producer's perspective, I tracked four lots of cattle sold at a feeder sale from the ranch through the saleyard process. Observation and producer interviews provided a description of attributes associated with grazing management, and livestock feeding and care.

Observation is frequently used in social science to understand the actions of individuals (Clark et al., 2009). Previous research has investigated how spatial, quality, and temporal factors have impacted cattle's price in the western United States by analyzing satellite video auction data (Saitone et al., 2016). Observation provides some additional context to price differences that may not have been revealed in data analysis research.

In addition to observation at the saleyards, I conducted semi-structured interviews with auctioneers ($n = 2$), cattle buyers ($n = 3$), and bay area ranchers ($n = 16$). Interviews were conducted within 1 week. Bay Area ranchers who sold cattle at the sale were randomly selected and interviewed via telephone. These ranchers sold between 15 and 161 head, with a combined total of 1,445 head of steers and heifers. Each interview was structured around two questions: (1) the reasons for selling/buying at the recent market and (2) how they felt selling impacted conservation objectives. I asked auctioneers about the buyer's interests and preparation of sellers. All responses were recorded in writing during the interview and imported into MAXQDA 2020, which was used to code and categorize responses (VERBI Software, Berlin, Germany).

Rancher Surveys

The majority of California ranchers are small, cow-calf producers—78 percent have <50 head ([USDA] United States Department of Agriculture, 2017). I mailed a questionnaire to ranchers located in four counties in the San Francisco Bay Area who sold <50 head during the year (2018). The four counties

TABLE 2 | Beef and dairy cattle contributing to beef production in California by age class for 2017 and 2018 based on movement from grazing lands and dairies.

	Cows				Steers and Heifers			
	Beef		Dairy		Beef		Dairy	
Type of Movement	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**
Grass out of state[a]	52,345	55,003			110,856	118,544		
Grass in State (sale)					50,350	36,914		
On feed	6,536	5,937	25,633	11,982	590,215	651,110	795,075	817,994
Saleyard	118,407	136,127	492,805	509,961	352,384	402,152	228,658	233,345
Wholesale/retail meat	20,154	28,276	299,620	318,767	7,327	14,025	37,381	51,100
Direct Marketed	3,241	5,745	171	100	20,550	19,328	1,927	1,681
Grand Total	**148,338**	**176,085**	**818,229**	**840,810**	**1,128,327**	**1,238,767**	**1,063,041**	**1,104,120**

[a]*Not included in grand total.*

sampled included Alameda, Contra Costa, San Mateo, and Santa Clara counties. Producers in these counties use a mix of private and public rangelands. Access to irrigated or improved pastures is minimal, similar to the statewide availability of irrigated pasture (**Table 1**). The questionnaire was mailed to 465 ranchers in December and March 2019, following the Dillman Total Design Method (Dillman, 2007).

To improve the response rate, I sent out a total of 4 mailings over 2 months: the full survey was sent twice, and two reminder postcards were sent. One hundred and thirteen people returned the questionnaires, representing a 27 percent response rate after accounting for undeliverable questionnaires. The questionnaire was an 8-page booklet with 12 questions. Ten questions were closed-ended, with categorical or Likert scale response choices. I used categorical questions to collect information about rancher experience, ranch size, and marketing choices. Ranchers rated their agreement with a series of statements about why they graze cattle, why they sold cattle using a particular method, and how they manage grazing. Their answers ranged from "completely disagree" (1) to "completely agree" (6). I presented the resulting Likert data as median scores. Figures were developed using Tableau Desktop Professional Edition 2018.1.

RESULTS

Cattle Movement Patterns

Beef cattle have an extensive footprint on the California landscape, where grazing lands contribute just over 1.1 million steers and heifers, and 150,000 beef cows to beef production in 2017 (**Table 2**). Beef cows were counted as contributing to beef production if they were moved to a saleyard, feedyard, or a meat processing plant; however, cows sold at saleyards during special female sales were excluded. Beef cattle from medium and small producers are found on grazing lands in every county in the state but San Francisco (**Figure 2**).

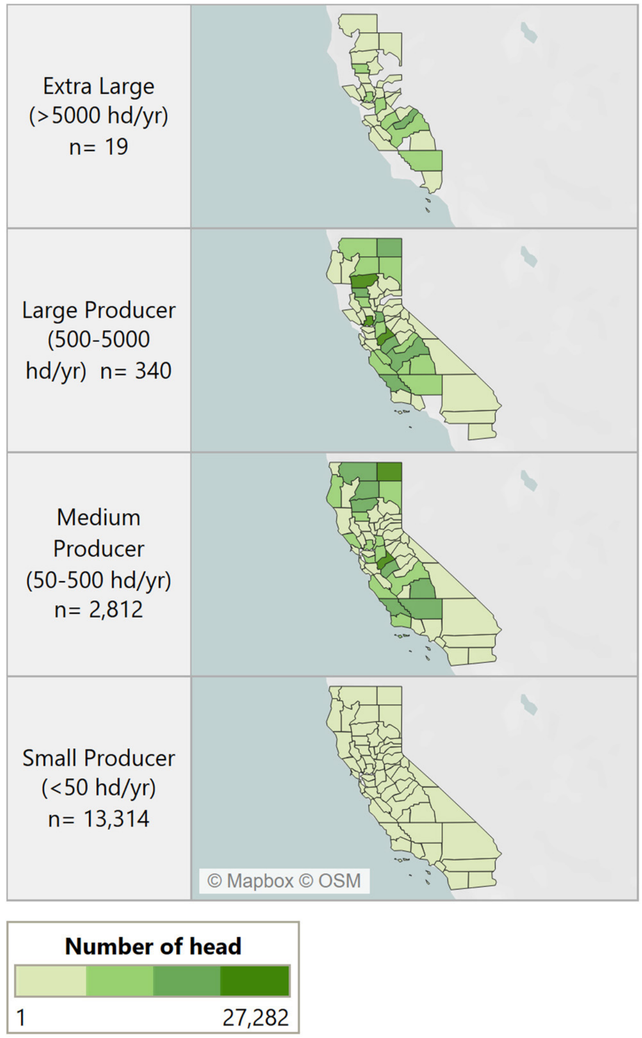

FIGURE 2 | Origin of all beef cattle from California (by county) moved from grazing lands by producer size (2017).

The movement of beef cattle from grazing land in California in 2017 and 2018 has a distinct seasonal pattern (**Figures 3**, **4**). Forty-seven percent of beef steers and heifers (calves and yearlings)—533,583 head that moved off California's grazing lands in 2017—were moved in late spring to summer—May through July (**Figure 3**). A smaller flush of movement occurred in the fall, October through November 2017, when 16 percent or 181,352 head of beef cattle calves were moved from grazing lands, typically but not exclusively from herds in the cold desert steppe where winters are snowy.

The seasonal pattern is similar for beef cows in that 51 percent of beef cows moved in 2017 left California grazing lands from May through July 2017 during the dry season on California's rangelands (**Figure 4**). Beef cow movement includes cows headed to grazing land out of state and those headed to saleyards, feedyards, or meat processing. Data is not readily available to accurately track the movement of cattle back on to California grazing lands. However, presumably, the beef cows leaving for grazing land out of state with no change in ownership return to California in the fall in anticipation of the Mediterranean annual rangeland's growing season. In 2017, cows leaving for grazing land out of state with no change in ownership described 96 percent of the 52,345 beef cows that left for grass out state. This movement of cows back and forth between grazing lands in California and Oregon has been previously documented by the United States Department of Agriculture, Economic Research Service (Shields and Matthews, 2001).

The seasonal movements of around 1.1 million head of beef cattle are in contrast to the nearly 2 million head of dairy cattle, which are also moved through production systems and contribute to beef production, but with little indication of any cyclical or seasonal pattern (**Figures 3**, **4**).

Types of Cattle Movements

In California, growing cattle (steers and heifers) are generally moved from an extensive grazing system to a more intensive production system for continued growth and finishing. On the other hand, culled beef cows are sent from grazing lands directly

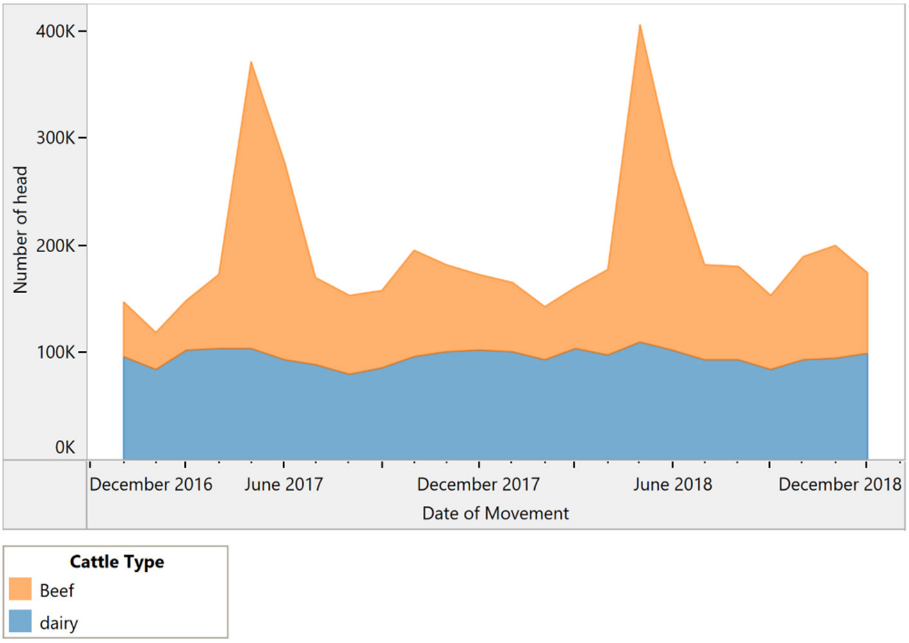

FIGURE 3 | Steers and heifers (number of head) moving from California grazing lands (beef) and dairies or feedyards (dairy) from January 2017 to December 2018.

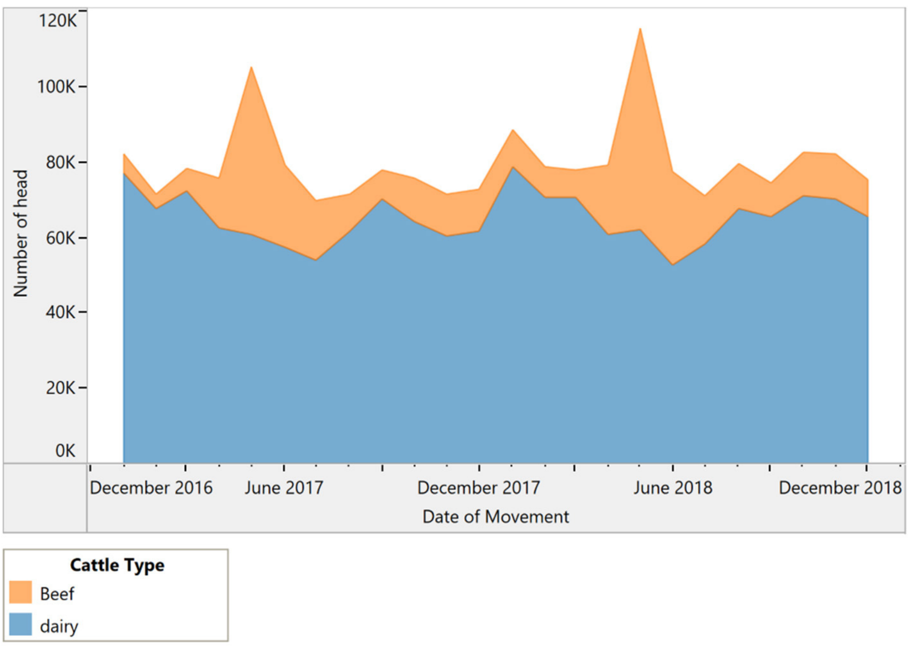

FIGURE 4 | Cows (number of head) moving from California grazing lands (beef) and dairies or feedyards (dairy) from January 2017 to December 2018, includes beef cows moved to grass out of state.

to processing, most frequently through a saleyard (**Table 2**). Saleyards also facilitate the movement of many steers and heifers to more intensive production systems (**Table 2**), but they also may be moved off rangeland through direct sale to a buyer or another producer. Some producers will move cattle and retain ownership. Among small- and medium-scale producers, producers retain ownership of 79 percent of cattle moved to grass out of state, whereas the largest producers retain ownership of 95 percent.

In contrast, retained ownership in the feedyard is most common only among the largest producers. Small- and medium-scale producers, retain ownership in the feedyard of ∼25 percent

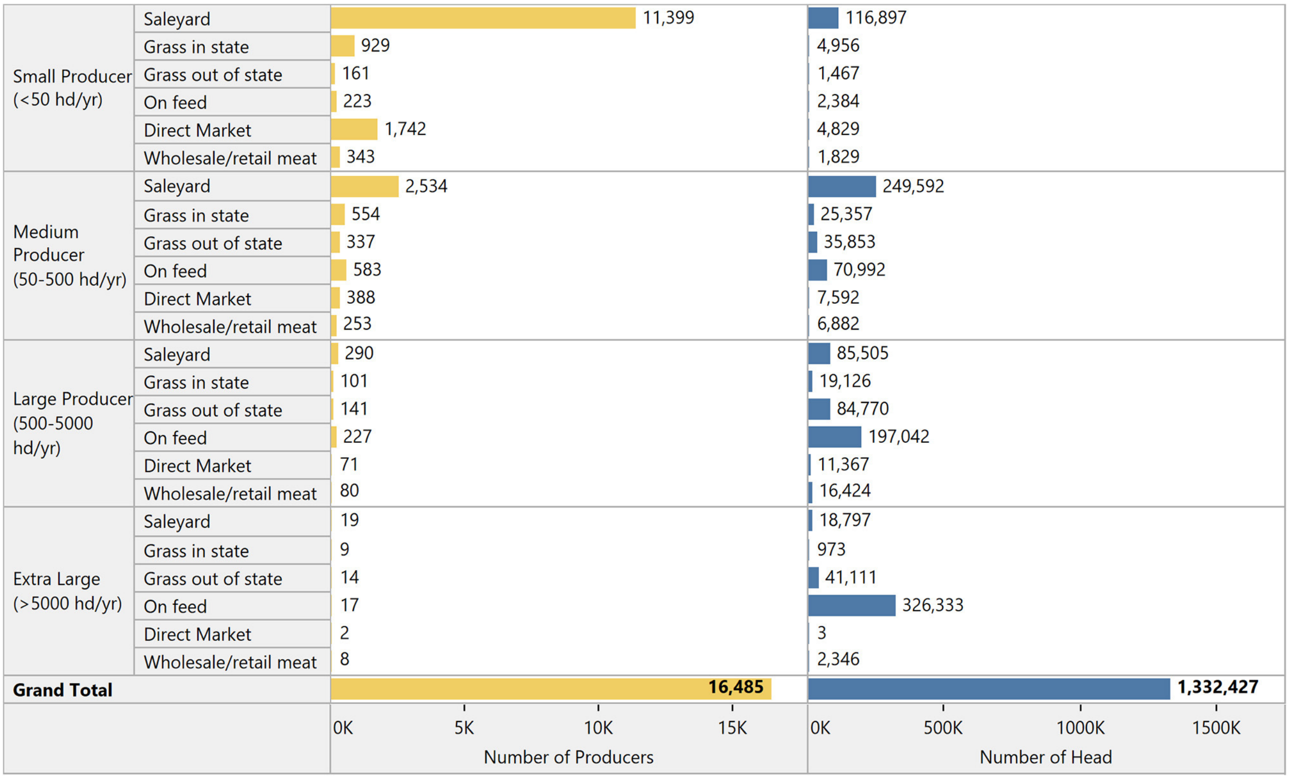

FIGURE 5 | Movements of beef cattle in California by size of ranch producer and destination from grazing land (2017). Size is based on total number of head but producers may use more than one type of movement.

of their cattle, and large producers retain ownership of 49 percent. The seven extra-large producers (more than 5,000 head of cattle) retain ownership of 90 percent of their cattle moved to feedyards.

Thirteen percent of all producers with beef cattle retain ownership of at least one animal all the way through processing. They may sell meat directly to consumers, known as "direct marketing," or keep it for household consumption (**Figure 5**, **Table 2**). However, the number they process for direct marketing or household consumption is small, 23,791 head of cattle, or <2 percent of all beef cattle produced in 2017 (**Table 2**).

Whether through retained ownership or sale, most beef cattle leaving California's grazing lands move into more intensive production systems or move directly to slaughter in the case of beef cows. Many cattle go to feedyards in Colorado, Nebraska, Kansas, Oregon, or grazing land, mostly in Oregon, Wyoming, and Nevada (**Figure 6**). Some of the beef steers and heifers from California's Mediterranean grazing lands may continue to graze extensive grazing lands or rangeland in locations with a summer growing season like Wyoming or Colorado (**Figure 6**). However, there is no data readily available to determine if cattle are moved to rangeland or improved pasture. This movement data also does not include intrastate movements when cattle are moved between fields without a change in ownership; nonetheless, 1.13 million head of beef steers and heifers were tracked in these data for 2017. Based on USDA cattle inventory data, the movement data includes 79 percent of California beef steers and heifers ([USDA] United States Department of Agriculture, 2017) since most are sold or moved out of state.

For all but the very largest producers (**Figure 5**), saleyards support most cattle movement from grazing lands. Small and medium-sized producers marketed nearly 70 percent of their cattle through a saleyard (**Figure 5**). Survey data from small-scale bay area ranchers revealed broad agreement that the saleyards (auctions) provided a fair price for their cattle (**Figure 7**), even though, for some, the saleyards are not nearby. Saleyards are dispersed throughout the state, with the larger saleyards located in the Central Valley near dairy cattle production, processing, and transportation corridors (**Figure 8**). The movement of cattle from the saleyards is not included in cattle movement data from California brand inspectors. However, based on the buyers' interest at feeder sales in 2019, most steers and heifers sold at the saleyard were purchased by a few large volume buyers and are moved into more intensive production systems.

Mature culled cows account for most cattle that are moved directly from California's grazing land to a meat processing facility. Culled beef cows mostly reached the meat processing facility after being sold in a saleyard (**Table 2**), where meat processors or their agents purchase them. Approximately 140,000 beef cows from California's grazing lands were processed for beef in 2017, representing a replacement rate of 18 percent for beef cows based on California's beef cow inventory ([USDA] United States Department of Agriculture, 2017).

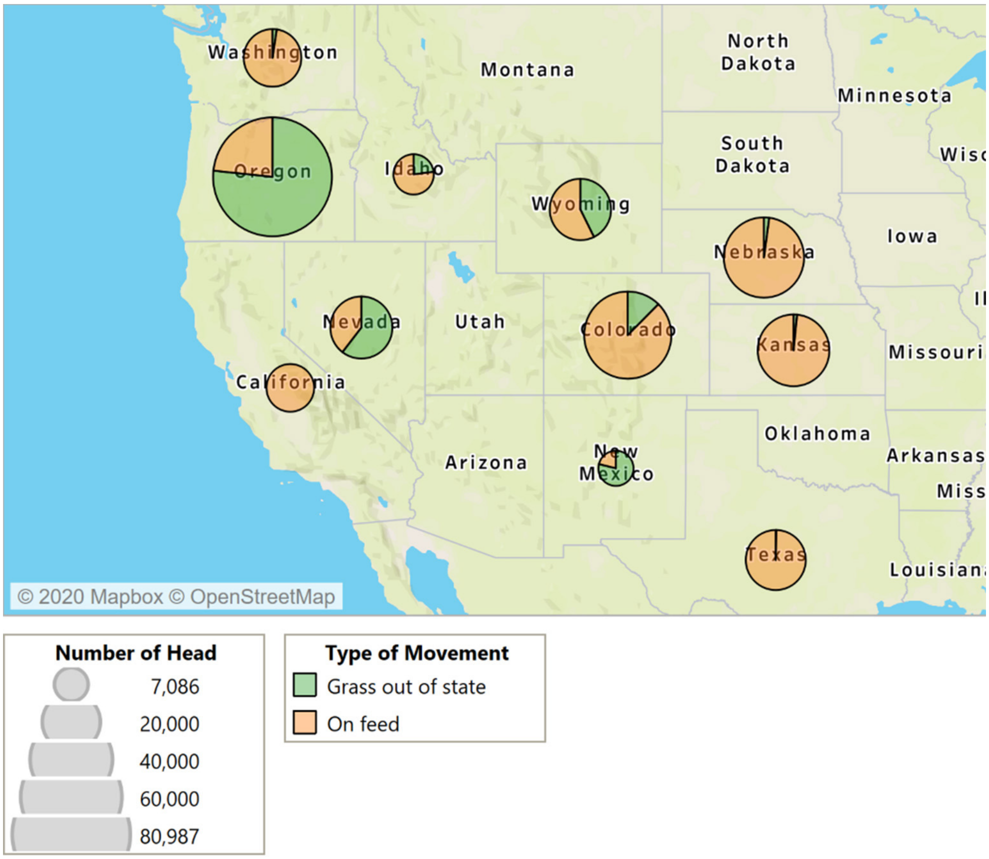

FIGURE 6 | Destinations of beef cattle traveling from California grazing lands to grass (out-of-state) or to feedyards (2017), excludes cattle sold at saleyards.

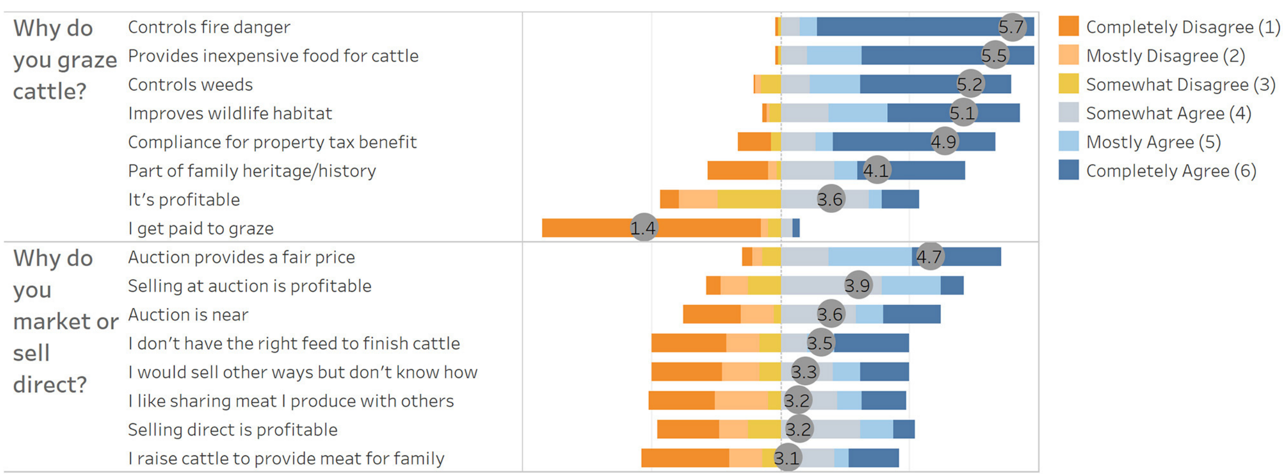

FIGURE 7 | Reasons small-scale beef producers in the San Francisco Bay Area, California graze cattle and sell at auctions or market directly, survey responses.

In addition to the cows moved from grazing land to processing facilities, the cattle movement data documents transhumance, at least when it occurs across state lines. Approximately 50,000 cows, some with calves, left annual rangelands in California in the late spring for grazing lands in Oregon, where there is green summer rangeland or irrigated pasture.

Factors Driving Cattle Movements

San Francisco Bay area ranchers selling calves and yearlings at feeder sales in May, June, and July in 2019 reported forage quality and quantity as influencing the time they chose to sell their calves or yearlings (**Figure 9**). Statements from Ranchers 4 and 15

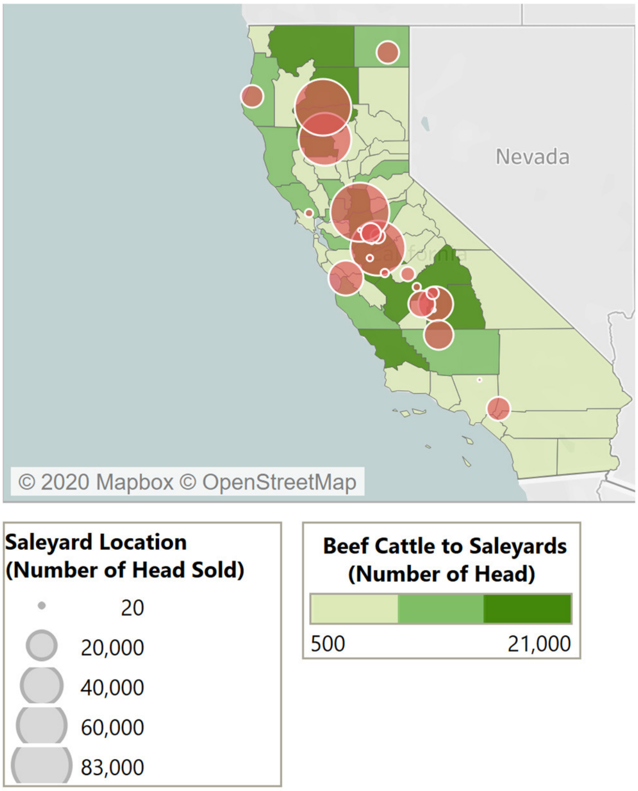

FIGURE 8 | Origin of all beef cattle from California (by county) sold at saleyards with location of sale yards and number of head sold in 2017.

acknowledged the change in feed quality and its impact on animal performance:

> *"This is the typical time of year to sell fall-born calves. You could keep them longer when feed is abundant, but calves do not grow well."*
>
> *"The feed turns this time of year and does not give calves what they need to grow. I retain feed [forage] for the cows."*

In terms of forage quantity, ranchers like Rancher 5 noted the importance of leaving feed (forage on the ground) through the dry season:

> *"We pull the calves and move the cows, so there is feed to come back to."*

When asked how selling at this time impacted conservation objectives, most ranchers spoke about conservation in terms of a desire to prevent overgrazing (**Figure 9**). Ranchers also acknowledged how their grazing management, including livestock sales, worked to support specific conservation interests. For example, Ranchers 7 and 15 recognized the value of grazing management to provide habitat for federally-listed threatened and endangered species:

> *"I take cattle off to rest the pasture during the summer. My grazing is compatible with the California red-legged frog, fairy shrimp, and the giant garter snake. I do not overgraze."*
>
> *"I have no conservations restrictions, but I keep it the best I can. According to the [United States Department of Agriculture, Natural Resources Conservation Service] NRCS biologist, it remains a good habitat for red-legged frog, California tiger salamander, and San Joaquin kit fox. I sold later than usual because I had excess feed, but there was no impact [to conservation]. I don't like to graze to the ground."*

Rancher 11 described how moving cattle, including the timing of sales, reduced fire risk, and protected soils.

> *"It was good to keep calves a little longer. I graze, so it does not burn. I graze closer [to the ground] next to property boundaries since my neighbors don't graze and have grass six feet tall. I keep cows and calves out of the hills during the rainy season to avoid erosion. After the rainy season, I jump [the cow and calves are moved] back and forth between hill and flats."*

Rancher 14 also stated how grazing management (selling) could protect soils.

> *"I sold because we were short of feed [forage]. I leave feed for the following year to come back to. Leaving feed to come back to also helps us with erosion on hillsides."*

A common theme among the ranchers was a commitment to good grazing management regardless of land ownership or conservation requirements. This view was clearly articulated by Ranchers 2 and 16:

> *"I have no directive for conservation, but as all cattlemen, I convert grass to beef, so we need to manage grass. . . I manage it (public and private), all the same, to keep grass."*
>
> *"I graze all lands (public and private) similarly. If you take care of the land, it takes care of you."*

Indeed, there are straight economic considerations that influence when ranchers move (or sell) cattle from California grazing lands. However, in rancher interviews, even economic reasons for selling, like changing market conditions or the need for cash, typically were explained within the context of forage quality or availability, like Ranchers 1, 6, 13:

> *"The market was going south. I could save a little feed by selling now."*
>
> *"I was watching the market and needed cash. I only marketed the heavy end because I have grass [irrigated pasture] for the lighter cattle to go on."*
>
> *"I had feed and prices were low, but I needed cash to pay bills."*

The balance of economic and ecological goals driving ranchers' decisions around moving (selling) is further exemplified by ranchers who spoke about retained ownership as a factor in selling decisions. Having access to quality forage to support yearling growth is key to a decision to retain ownership as exemplified by Ranchers 7 and 12:

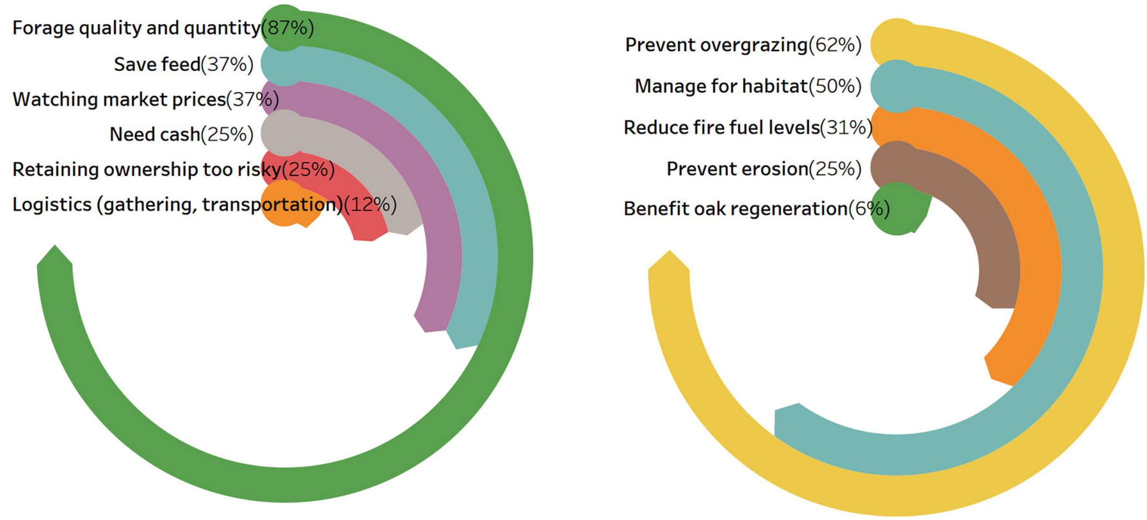

FIGURE 9 | Reasons for time of sale of calves and yearlings from grazing lands in the San Francisco Bay Area, California and expected conservation outcomes, based on interview responses.

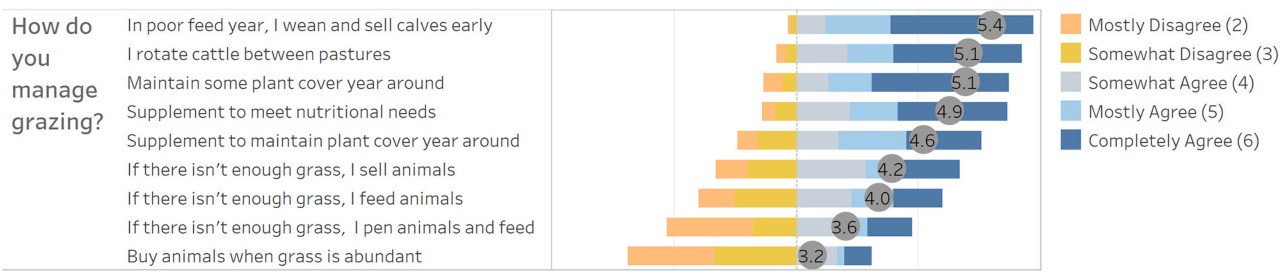

FIGURE 10 | Cattle grazing management by small-scale beef producers in the San Francisco Bay Area, California, survey responses.

> *"We used to sell calves, and now we retain ownership because we have [irrigated] pasture."*
>
> *"When we had permanent [irrigated] pasture, we would sell our calves as yearlings in November, but we lost that pasture, so now we sell our calves."*

A mix of economic and ecological interests was also illustrated in survey data from small-scale producers in the San Francisco Bay area (**Figure 7**). There was strong agreement with economic reasons for grazing, including it is *inexpensive feed* and it *provides tax benefits*, but also for ecological reasons such as *grazing controls fire dangers*, *improves wildlife habitat*, and *controls weeds*. However, very few of these producers regard *grazing as profitable*.

How small-scale producers in the San Francisco Bay area manage grazing also reveals information about factors driving cattle movements (**Figure 10**). Responses from ranchers suggest that their livestock mobility strategies, including rotating or moving cattle between pastures, are aimed at maintaining plant cover and meeting the livestock's nutritional needs, more than reacting to lack of available forage. Early weaning and selling calves is a favored strategy in poor feed years. In response to lack of forage, destocking or selling animals is only somewhat practiced by most producers, and few producers consider feeding.

Infrastructure Supporting Cattle Movements

Interviewed ranchers explained that transportation, saleyards, access to additional quality feed sources, and processing capacity all support cattle movements in California. Ranchers may use a pickup and gooseneck trailer combination to haul livestock to a market or move cattle between pastures. However, most also rely on professional livestock haulers that operate semi-truck and trailer combinations specifically designed to haul livestock. Haulers may transport animals from grazing lands to saleyards, and then to grazing lands or feedyards after they are sold. At the feeder sales, semi-truck and trailers were lined up to transport purchased cattle, and after a winning bid, buyers assign lots of cattle to different groups for transport. Livestock haulers are also required for the final transport to a processing facility. The value of transportation to managing grazing lands was acknowledged in the survey of bay area ranchers. When asked about future challenges to managing their grazing lands, some ranchers noted that recently proposed federal regulations regarding hours of service by truck drivers as well as state regulations requiring newer vehicles that met emissions standards may limit the availability of livestock haulers and increase transportation costs and could impact ranching sustainability.

While transportation is required to move animals for production system integration, sale yards facilitate matching livestock with a production system. Saleyards are the primary marketing method for most small and medium-size producers (**Figure 5**). They allow producers to market all classes and types of cattle. At a saleyard, buyers come together to bid on cattle providing current market price through competitive bidding. The saleyard may sort cattle from a seller into lots of similar size and kind. Buyers put together loads of similar cattle from different sellers. The sorting and grouping of cattle conducted at a sale yard can add value. For example, small groups of cattle may receive a more competitive market price when combined to make a load of cattle.

Cattle buyers utilized specialized knowledge gained through experience to choose cattle at the feeder sales to go back on grass or into a feedyard based on age, weight, breed, sex, and geographical origin. Buyers are looking for certain types of cattle to fit specific forage or feed conditions available to them, and some clear patterns can be observed. Recently weaned, lighter cattle are more likely to go back to feeding on grass, including irrigated pasture, while yearlings or heavier cattle may go directly to a feedyard. Breed type may also influence cattle destination. One buyer noted that he would no longer put black-hided cattle on feed in Colorado because of his experience with a higher incidence of a brisket disease, a genetically-transferred heart disease that impacts cattle at higher altitudes.

Buyers learn about cattle through written, visual, and oral information during the sale (**Table 3**). Some information such as weight, sex, breed, and vaccinations support premium prices or result in discounted prices relative to other cattle. Based on the ranch name and location, reputation may also influence the price or even a buyer's interest in bidding. A buyer may be willing to pay more if he knows that cattle from a particular producer perform well.

Buyer's decisions are not only influenced by the supply of cattle at the market but also by the available forage or feed, or processing capacity. For example, one buyer remarked that he was placing fewer cattle on grass because there were far fewer acres of irrigated pasture available in the Klamath Basin, Oregon than 5 or 6 years ago. Instead, he was buying cattle to place in a feedyard in Washington, where by-products from processing potatoes and distillers grain keep feed costs down.

Little information is provided to buyers about managing the cattle or feed resources, including grazing management. Grazing land management that provided ecosystem services, including conservation of wildlife habitat or watershed protection, is not attributed to the cattle. Ranchers surveyed in the San Francisco Bay area overwhelmingly disagreed with the statement that "they are paid to graze" (**Figure 7**). Nevertheless, bay area beef producers can identify ecosystem services that they attribute to their grazing management (**Table 4**). Cattle buyers moving cattle into more intensive production systems also recognize resource management practices such as feeding by-products and animal welfare practices such as low-stress livestock handling that they provide without attribution (**Table 4**). Unless cattle are associated with a specific-value added program (e.g., natural, organic, source-verified), information transferred through the production systems is limited to physical details that can be visually assessed or measured, such as weight, color, sex, frame size, and hot-iron brand if available (ranch origin).

DISCUSSION

Beef cattle graze throughout California (**Figure 2**), and most of the landscape they graze is rangeland. Like rangelands throughout the world, this land is often not suitable for cultivation, yet it supports livestock production. Arguably, extensive livestock grazing is not the most efficient production system in absolute terms of the number of head produced or livestock gains per hectare (Huntsinger et al., 2012; Tichenor et al., 2017). For instance, the California dairy industry provides more cattle—a larger number of culled cows—to beef production than beef cattle producers (**Table 2**), and they operate on a smaller land footprint in California (without considering land used out of state to grow their feed). However, extensive livestock grazing contributes to food production on land with limited to no ability to contribute otherwise (Reid et al., 2008). Perhaps, more importantly, rangelands are high in biodiversity and ecosystem service production, which can often be enhanced or protected with ranching (Huntsinger and Oviedo, 2014).

Beef Cattle Production on Extensive Lands Supports Conservation

Integrating extensive grazing systems with other production systems supports livestock production while maintaining extensive grazing lands in California. Integration provides alternative feeds resources to support production and allows ranchers flexibility to manage for multiple ecosystem services. Most ranchers seasonally move cattle, with many ranchers selling their growing calves or yearlings where they are finished in a more intensive production system. Ranchers surveyed overwhelmingly indicated that grazing provides inexpensive feed and serves to reduce fire fuel, control weeds, and improve wildlife habitat (**Figure 7**). Roche et al. (2015) showed a similar finding in a survey of California ranchers. Nearly all (97%; $n = 490$) agreed with the statement, "whenever possible, I try to conserve natural resources."

Conversion to other land uses, including cultivated agriculture, where feasible, has resulted in ongoing losses of rangeland in California (Sulak et al., 2008; Cameron et al., 2014), but intensification on grazing land is not a common practice. Rangeland improvement practices, including seeding, fertilization, and control of brush and trees, were tested and promoted by agricultural extension and government assistance programs beginning in the late 1800s to increase forage quality and quantity for livestock production (George and Clawson, 2014). However, since the 1980s, rangeland management in California has increasingly emphasized multiple goals, including

TABLE 3 | Information available to cattle buyers for feeder cattle from San Francisco Bay Area ranches and impact on sale price.

Attribute	Information Available to Buyers of Feeder Cattle			Sale Price Impact	
	Written	**Visual**	**Oral**	**Premium Price**	**Discount Price**
Number of head	Onscreen	Observed	No	Truck lots	Small number
Weight, frame	Onscreen, average weight	Observed	Announced, heavy end, light end	Light weight (230–270 kg)	Heavy weights (>385 kg) or small frame
Class (sex and age)	Sale catalog, if available	Observed	Announced sometimes	Steers	Heifers, bull calves
Color (hide), horns	Sale catalog, if available	Observed	No	Black hide	Horns
Breed	Sale catalog, if available	Observed, breed types	Announced sometimes		Dairy, Bos indicus features
Shots (vaccines)	If provided, Sale catalog, if available	No	If provided, announced	Two rounds of vaccines	No vaccine information
Ranch Name	Sale catalog, if available	Observed, brand	Announced sometimes	Reputation, performance history	
Ranch Location (town)	Sale catalog, if available	No	Announced sometimes		Coastal locations
Origin (ranch-raised or bought)	Sale catalog, if available	Maybe, brands	Announced sometimes	Reputation	
Sire information	If known, Sale catalog, if available	No	If known, announced	Reputation, performance records	
Weaning status	If occurred, Sale catalog, if available	No	If occurred, announced	30 day minimum	
Program (Natural, No Implants, Source verified)	Sale catalog, if available	Observed, ear tag	If applicable, announced	Eligible for export markets	
Feed (pasture type)	Sale catalog, if available	No	No		
Grazing Management	No		No		

TABLE 4 | Example of production attributes, identified by producers of beef cattle originating in the San Francisco Bay area, that are not tracked or shared through the integrated production system.

Class	Head	Producer 1 (Cow-calf)		Producer 2 (Stocker)	Producer 3 (Feed yard)
		Attributes presented at sale (auction)	**Attributes not shared**	**Attributes not shared**	**Attributes not shared**
Steer	61	Natural (no implants), At Branding: vaccinations and dewormer; Booster: vaccinations (Product names provided). Sorted off cow (not weaned)	Conservation grazing management program on public land. Grazing supports habitat for native flora and fauna, and reduces fire fuel loads	Irrigated pasture provides hunting grounds for wintering raptors and feed for migrating birds along the Pacific Flyway	Health program. Low-stress livestock handling. Daily ration includes food processing waste and agriculture by-products. Feedyard produces manure and bedding which fertilizes nearby field and vegetable crops

native species conservation and providing other ecosystem services (Spiegal et al., 2016). Supported by integration with other production systems, California's rangelands in public and private ownership remain as extensive grazed landscapes, covered with native or naturalized plants. Ranchers move cattle and manage grazing to support native biodiversity by reducing non-native plant species and accumulated residual dry matter, and increasing landscape-level diversity (Bartolome et al., 2014).

The value of maintaining extensive grazing lands to contribute to food production while providing multiple other ecosystem services is not unique to California (Curtin and Western, 2008; Reid et al., 2008). Grazing systems on different continents function in ecologically similar ways; conserving native and wildlife grazers, and many species associated with grazing lands, requires protecting extensive natural landscapes (McNaughton, 1985; Harris et al., 2009; Niamir-Fuller et al., 2012). While conversion of grazing lands to other land uses jeopardizes vast landscapes, interventions, or strategies purported to save rangeland or pastoral livestock production may also have negative consequences for conservation and ecosystem services. These strategies include ending extensive livestock grazing (e.g., Chinese grazing ban, Han et al., 2008), often along with encouraging pastoralists to settle and adopt intensive forms of agricultural production (Scoones, 1995; Flintan et al., 2011). Agriculture intensification increases yield per unit area, but settlement and agricultural intensification may do little to improve the well-being of the pastoralist or the condition of degraded rangeland. Intensification can lead to both more and less intense grazing—both factors that may adversely impact ecosystem services (Niamir-Fuller, 1999; Angassa and Oba, 2008). The loss of native biodiversity from the intensification of agriculture on grazing lands is documented, as is the threat to biodiversity and other ecosystem services from both over- and under-grazing (Milchunas et al., 1998; Mcintyre et al., 2003; Metera et al., 2010; Cameron et al., 2014) resulting from lost flexibility for grazing management and the failure to understand non-equilibrium systems (Ho, 2001).

With regards to agriculture intensification, pastoral management of non-equilibrium rangelands should not be confused with the management of improved pastures or pastures created by the conversion of native forested habitats to grazing land, like in the Amazon or New Zealand. On pasturelands that are developed by removing native forest, intensive management that includes rotational grazing, seeding of legumes and improved cultivars, and integration of livestock with cropping systems may be a viable strategy to spare native habitats while increasing agricultural output (Phalan et al., 2011; Latawiec et al., 2014). Intensification of rangelands, however, results in degradation and puts at risk resource values, including native biodiversity, which instead is often complimented or enhanced by the kind of managed grazing of pastoral systems that work with the natural environment (Niamir-Fuller et al., 2012; Alkemade et al., 2013; Cameron et al., 2014; Kaufmann et al., 2018).

Mobility Matches Cattle Production to Forage Resources

Ranchers expect and work with variability in forage quality and quantity by moving livestock across biomes and pastures and into other production systems, where forage or feed resources are available to meet livestock production needs. Moving cattle to different production systems is typical in the United States and in some other parts of the world where beef production occurs in three phases (cow-calf, stocker, finisher) (Nin et al., 2007). The three-phase system developed due to cattle's relatively long biological production cycle and the different resource and management needs for each phase of production; these same factors have been a disincentive to vertical integration (Ward, 1997). The three-phase system typically includes integration of grazing systems, which support cow-calf and stocker production, with intensive systems that finish cattle in a feedyard. For California ranchers, who manage non-equilibrium systems, these movements are timed to manage variability and fit forage resources. While ranchers are able to sell their calves into the next phase of production, the timing of the sale allows cattle to "fit" the resource, which is evident from the substantial seasonal movement of cattle from California's grazing lands (**Figures 3**, **4**). Based on rancher statements and similar to traditional pastoralists who move livestock to track forage resources, cattle movements are informed by livestock needs and changes in forage quality and quantity. On California's non-equilibrium rangeland, annual forage productivity varies unpredictably by a factor of three or more based on weather (George et al., 2001b). Where forage quality may be predictable based on season, the weather also creates uncertainty about the timing of the seasons (George et al., 2001a,b).

The seasonal movements of cattle from grazing lands align with seasonal changes in forage quality and quantity, particularly on California's annual rangelands. Bentley and Talbot (1951) defined three seasons, inadequate green forage, adequate green forage, and inadequate dry forage nearly 70 years ago. These descriptions are still used by rangeland managers to explain the seasonal patterns of California's annual rangeland as it pertains to supporting livestock production (George et al., 2001b; Becchetti et al., 2016). The onset of the inadequate dry season, which describes the summer's dry annual forage, corresponds with the movement of steers and heifers and some cows off California's annual rangelands. Although the annual dry forage provides some energy for grazing animals, it is low in protein, phosphorus, carotene, and other vital nutrients, and inadequate to support young growing animals without feed inputs or prolonging production time (George et al., 2001a,b). Mature beef cattle can be maintained during the inadequate dry season, though ranchers expect and manage cows, knowing they will typically lose weight and body condition (Renquist et al., 2006).

The new growing season begins with the inadequate green forage season in the fall.

Seeds stored in the soil from the previous year's growth germinate with fall precipitation. This season's onset and length depend on weather conditions, which creates uncertainty in determining carrying capacity. However, as the survey responses and interviews indicate, Bay Area ranchers stock to maintain dry forage through the summer, so they have feed to come back to. Residual forage helps ranchers manage the new forage season's unpredictable start and provides dry matter to support livestock during the "inadequate" green period. While dry residual forage is often low in protein and other vital nutrients, new green forage with its high-water content can inhibit livestock from consuming enough to meet their nutritional requirements–hence the name "inadequate green forage season" (Becchetti et al., 2016).

The final forage season, rapid spring growth, or adequate green forage begins with warmer weather in late winter or early spring, depending on precipitation. During this season, livestock performance improves, and the forage is nutritionally adequate for growth, maintenance, reproduction, and gestation. Livestock weight gains are highest during this period. Rapid spring growth continues for a short time until either plant growth is limited by a lack of soil moisture or plants mature. Peak standing crop marks the end of the rapid spring growth season (Becchetti et al., 2016). In a study at a research center in the Sierra foothills of California, Raguse et al. (1988) found that average daily gains of yearling cattle increased from December to early May and then rapidly decreased. Rancher's decisions to move growing animals off the rangeland in late spring, early summer reflects this seasonal decline in forage quality. Controlling the rapid spring growth with grazing also benefits native species conservation (Bartolome et al., 2014).

The seasonal movement of steers and heifers, and cows from grazing lands in the fall (**Figures 3**, **4**) also corresponds to weather and forage changes. These movements are typically associated with forage changes in California's high elevation cold desert steppe and warm desert range. Both cold desert steppe and warm deserts, which are primarily federal land, managed in partnership with the United States Forest Service (USFS) or the Bureau of Land Management (BLM), have relatively low numbers of grazing livestock. However, movement allows ranchers to graze ephemeral forage as well as shrubs and native perennial grasses (Huntsinger and Bartolome, 2014). Cattle may be herded by ranchers within the leased land, or lead cows with knowledge of the range will move cattle to good foraging locations.

Transhumance, the seasonal movement of cows, has been documented within California and between California and Oregon, Nevada, and Idaho (Huntsinger et al., 2010). Although the seasonal movement of cows between the cold desert steppe or warm desert range and ranches on California's annual rangelands was not captured in the inspection data, the data shows over 50,000 cows (7% of the state's cow herd) moving from summer pasture to neighboring states from California's rangeland.

Managing grazing lands by fitting livestock needs to the environment was also documented among California ranchers in Roche et al. (2015) study. They found that the highest-rated ranch management practice was "matching calving to the environment." Matching calving to the environment sets up ranchers to market or move weaned calves off grazing lands when the rangeland becomes insufficient in quality to meet a growing animal's needs. For example, calving near the beginning of the growing season, the period of inadequate green forage, means that a beef cow will reach peak lactation as her growing calf becomes ready to take advantage of the abundant, high-quality forage during the rapid spring growth season. Roche et al. considered this practice an aspect of economic sustainability. Moving growing cattle off rangeland by selling them is a management strategy. California's ranchers use for managing the interannual forage production cycle inherent in non-equilibrium rangeland. It should not be confused with destocking, which is selling to reduce stock numbers in response to an unexpected loss in forage production from an event such as drought (Morton and Barton, 2002). Droughts and wildfire have forced some California ranchers to destock or feed (Macon et al., 2016).

Decisions regarding the movement of livestock on grazing lands by California ranchers in transhumance and through trade are not unlike decisions that pastoralists have made for centuries where livestock needs are matched with forage to take advantage of the variable climates impact on vegetation (Fernandez-Gimenez and Le Febre, 2006; Krätli and Schareika, 2010). Like pastoralists, ranchers use their knowledge of their environments to manage resource use (Niamir, 1995; Fernandez-Gimenez, 2000). Whether within ranges or between biomes, seasonal weather patterns, forage growth, and livestock nutrition and production requirements typically guide livestock movement—although increasingly pastoralists and ranchers may be required to move animals in response to societal influences, such as landowner requirements, political boundaries, land-use changes or designation. Ranchers' ability to either move or sell livestock into another production system might, in some part, compensate for required movements or loss of access to some grazing lands.

As with many tools used for pastoral development (Krätli, 2016), equilibrium thinking misinforms some rangeland management policies and practices on California non-equilibrium rangelands. For example, some public agencies and NGOs have removed livestock grazing from lands they manage (Fried and Huntsinger, 1998), and now with conservation values, including native species habitat loss, they struggle to put grazing back (McGarrahan, 1997; Barry et al., 2015). Moreover, most public grazing contracts often set fixed stocking terms and charge ranchers a set price per animal unit month (AUM), each of which fails to account for inter- and intra-annual variability in forage quantity and quality. This pricing creates a problem when a public landowner wants a rancher to extend grazing time or increase stocking rates on low-quality forage and continue to pay the set AUM rate for forage that does not meet livestock production needs (Becchetti, T. email message to author October 5, 2019).

Equilibrium assumptions also influence ideas about improving ranching's economic viability. Like in most pastoral societies, ranching is an economically marginal activity (Wetzel et al., 2012). Marketing a ranch-raised product at a higher price has been promoted as a strategy to increase returns from grazing lands (Huntsinger et al., 2010; Forero et al., 2014). Based on retail sales of labeled grass-fed beef, which grew in the US from $17 million in 2012 to $272 million in 2016, there is a growing market for direct sales from ranch-to-fork (Cheung and McMahon, 2017). While California ranchers could market ground beef from ranch cows, a type of animal the grass-fed industry describes as "default grass-fed," accessing enough quality forage year-round to grass finish steers and heifers on California's rangeland is a challenge because of the seasonality of both forage abundance and forage quality on California rangelands. Ranchers like pastoralists specialize in taking advantage of the environmental variability- this management allows them to improve productivity (Krätli, 2016). It is also difficult for producers to compete with cheaper imported grass-fed beef or beef from grass-feeding operations. In other words, working within California's non-equilibrium rangeland system to find forage on other grazing lands, or feed in another production system to finish growing animals, best provides for livestock production and rangeland management.

Integrated Production Systems Facilitate Mobility

Livestock grazing systems have been classified in ways that describe both the management of livestock and the social structures of the people that own and manage them, including pastoralism, transhumance, and ranching. In each of these cases, the system is based on some form of matching seasonal and annual forage availability to livestock production needs within the context of the forage resources available to producers and the producers' social needs. The integration of extensive grazing systems through transportation, and through trade with intensive production systems, effectively expands the capacity of the beef production system without sacrificing livestock grazing systems and their associated benefits.

In the literature, grazing and confined animal feeding are often considered independent types of production systems, as in Tilman et al. (2002, p. 675), "Pastoral livestock production makes extensive use of ecosystem services and eliminates many of the problems of confinement production." Also, the introduction of feedyards and processing plants and other capital infrastructure is considered to "commercialize livestock production" (Fratkin and Mearns, 2003) as well as require all producers, including small-scale to standardize production (Lundström, 2019). However, as illustrated by the beef cattle production system in California and practiced in many other parts of the world (Krätli et al., 2013), grazing and confined animal feeding are not mutually exclusive. By selling an animal at a saleyard, even a rancher in California raising one head on grazing lands can participate in the integrated production systems, with little to no standardization of production. Market integration allows even small-scale ranchers with extensive livestock production systems to produce a marketable product.

Most ranchers in California, from the small producers (<50 head) to the extra-large producers (more than 5,000), participate in the integrated beef production system. Less than 1% of steers and heifers go from rangeland to meat processing, and <2% are direct marketed. While the largest ranchers are more likely to retain ownership through finishing, small- and medium-scale producers can also retain ownership. Retained ownership has been promoted to cow-calf producers by agricultural economists because of its potential to increase returns; however, producer's aversion to risk has been shown to limit retained ownership among cow-calf producers (Pope et al., 2011). Backgrounding or preparing calves for feedyards by weaning and introducing cattle to feed is a practice that leads to increased retained ownership (White et al., 2007), but most California ranchers manage extensive rangeland with no such facilities. As noted in the premiums paid for California calves (**Table 3**), buyers are willing to pay a premium for calves weaned for 30 days as many show up to the saleyard having just been removed from the cow.

While the beef production system is not generally vertically integrated and the supply chain phases operate independently, the integrated system transfers beef production decisions and opportunities from extensive grazing systems to more buyers and producers operating more intensive production systems. These producers also determine the final product produced for meat processing. However, besides supporting grazing management, selling calves can transfer the market risk of owning stockers or feeders, allowing ranchers to focus production on calf production, where market prices are relatively more stable (Brownsey et al., 2013). Larger producers may be better able to weather the risk of owning stockers and feeders but do not necessarily increase their profits from retaining ownership through these phases of production (Langemeier, 2019).

Small- and medium-scale producers in California almost exclusively rely on trade (selling at the saleyards) to support livestock moving off rangelands. However, even among all the largest producers (more than 5,000 head, $n = 19$), saleyards are used to sell at least some cattle. When large producers do not retain ownership, they often market their cattle in large lots directly to a buyer. The importance of saleyards and the buyers, who match cattle with other grazing or feed resources, cannot be overstated. The ability of saleyards to market all classes, quality, and types of cattle provides an opportunity for ranchers to effectively utilize forage for livestock production and meet other resource management objectives. Ranchers indicated that selling cattle from grazing lands helped prevent overgrazing, manage for habitat, and in some cases, reduce fire fuel loads, prevent erosion, and support oak regeneration (**Figure 9**). Mobility provided by the saleyards and integration of production systems optimizes the use of forage on rangelands beyond the boundaries of discrete operations. Ranchers use the saleyards and buyers to create value from rangeland by contributing to the production of a marketable product.

While saleyards are used by ranchers to facilitate livestock mobility, the saleyards and cattle buyers also drive production efficiency by sorting cattle and matching them to feed resources. Most of the attributes of interest to cattle buyers at feeder sales relate to potential efficiency in terms of rate and cost of weight gain (**Table 3**). Discounting heifers, small frames, and exotic crosses (*Bos indicus* features) is a penalty for less efficient animals. These cattle generally grow slower and yield less than a medium, crossbred steer ([NRC] National Research Council, 1996). They are also less likely to produce a high-quality carcass. Premiums or higher prices for vaccinated cattle from reputable producers reflect the expectation of higher performance. Buyers want cattle that can get off to a better start with fewer health problems. Improved efficiency can reduce the cost for producers growing and finishing cattle and minimize resource use and greenhouse gas emissions (Capper, 2011; Herrero et al., 2013; Becoña et al., 2014). No premiums are provided for conservation values provided by grazing management and rancher stewardship but, by default, discounts on market prices related to efficiency serve as an environmental impact fee to the producer.

A drive to maximize production efficiency in the beef production system can go too far and negatively impact livestock production communities and environments. As previously noted, extensive grazing systems that support natural plant communities are not inherently the most productive. Forcing these systems to maximize production or failing to recognize non-production values of managed livestock grazing will put high-value natural ecosystem services at risk. For example, China has been promoting a "sustainable livestock industry" by intensifying all phases of livestock production. In 2002, the Chinese government required the removal of 30 million head of livestock from 92 million hectares of grazing land. The "grazing ban" was implemented to restore degraded rangeland and support sustainable intensification. To compensate pastoralists who lost grazing lands, the Chinese government provided them grain and feedyards to raise their livestock. Meanwhile, researchers in China are working to identify and develop livestock genetics that will yield more meat under an intensive production system. The grazing ban has changed ethnic pastoralists' lifestyles, who have been stewarding the grasslands for generations. Ecological impacts from the grazing ban to the grassland ecosystem, which has evolved over thousands of years with pastoralist and livestock grazing, are uncertain (Han et al., 2008; Cheng et al., 2011; Li and Huntsinger, 2011). Balancing production efficiency with ecological interest requires a comprehensive understanding of production systems, including their integration with other production systems and policies that recognize non-production values, including many ecosystems services.

Even though ranchers surveyed in this study mostly agreed that saleyards provided a fair price, it is evident that ranchers continue to be price takers. Furthermore, conservation values and ecosystem services ranchers provide with managed grazing are not generally recognized and not easily reflected in prices. Landowners, including public agencies that lease rangelands to ranchers, may directly benefit from these ecosystem services and, therefore, may be willing to accept lower fees from ranchers. However, in practice, the market for rangelands for grazing in California is tight enough that lease rates are often still high ([CASFMRA] California Chapter American Society of Farm Managers Rural Appraisers, 2020). Some consumers may be willing to pay more for products associated with grazing for conservation benefits; in practice, the certification process and marketing can be expensive. The production system is also not well set up to otherwise label final products with the origin or production practices (Woodard, 2014). Since ranchers primarily produce calves and yearling and, as a by-product, mature cows and bulls, it is difficult for them to connect their production and management efforts with beef consumers. High rent, low margins, and competition in beef calf production from both other rangeland-based producers and the dairy industry tend to lead ranchers to subsidize their ranch with off-ranch income (Smith and Martin, 1972; Torrell and Bailey, 2000).

While income from rangeland livestock production may not be the primary driver for many beef cattle producers, their economic sustainability is considered critical to conservation. There is growing interest in valuing ecosystem services from rangelands and from pastoralism and pastoral livestock (Plieninger et al., 2012; Silvestri et al., 2012; Hoffmann et al., 2014), and incentivizing or paying pastoralists and ranchers to provide them (Davies and Hatfield, 2007; Sayre et al., 2012). The integrated production system that currently creates value for livestock products for California ranchers fails to capture the value of these services and obscures them as their ranch-raised cattle are feedyard finished and mixed with beef from other production systems, including dairy beef. Current value-added programs for meat products like natural, organic, or grass-fed are limited in beef production attributes that are accounted for and promoted. Marketing beef with specific credence attributes requires transferring verifiable information (Caswell and Mojduszka, 1996; Umberger and Feuz, 2004).

Blockchain to Support Integrated Markets

New data technologies promise to support the transfer of information through an integrated production system, which could allow ranchers to document different attributes of their cattle's care and health and their stewardship of resources (**Table 4**). Tracking beef through the entire production system (e.g., from ranch to fork) is possible when individual animal ID is coupled with new data technologies. Blockchain, developed as a ledger for bitcoin, connects transactions with timestamps and transaction data to keep data linked. Its creation of a time-data chain allows for information like where and when an animal was born, how it was fed or grazed, what vaccines it received, and where and when it was transported to be tracked with the animal.

At least four beef production projects have been conducted demonstrating this technology's ability to provide transparency and transfer information through beef's integrated production systems. McDonalds conducted the first test of blockchain to track and verify cattle management through the supply chain in 2016 (McDonalds, 2017). They demonstrated proof of concept by tracking 8,967 head of Canadian cattle produced with sustainable practices—this pilot project represented 1 day's supply to McDonalds restaurants in Canada. Sustainability practices verified included maintaining well-managed grazing systems, implementing management plans to protect water and waterways, adhering to animal welfare practices, and supporting local rural economies.

Another pilot project was conducted by JD.com, a major Chinese e-commerce site. This project was focused on restoring consumer confidence in food safety and providing transparency about the origin of meat products. In May 2017, JD.com used blockchain to track meat from beef producers in Inner Mongolia to consumers in Beijing, Shanghai, and Guangzhou. Consumers were provided with information, such as the cow's breed, slaughter date, and what bacteria testing it went through. Then in March 2018, JD.com began tracking the production of Angus-beef sourced from farms in Australia. Blockchain data assures customers that only Angus beef from Australia is sold under a specific label (Zhao, 2018).

Other aspects of livestock production are also being tracked and shared with consumers with blockchain. In Fall 2019, Wong, a supermarket chain in Peru, partnered with SUKU, a Silicon Valley, California-based company, to use blockchain to cover all meat products sold in 20 stores. The products are stamped with SUKU, meaning that the product has been tracked from pasture to shelf; the blockchain platform allows customers to view the animal and meat's history, including animal health treatments (Ashgar, 2019).

In 2019, BeefChain, the first blockchain company to receive certification from the United States Department of Agriculture (USDA) as a Process Verified Program (PVP), began selling products. The USDA certification allows BeefChain to audit ranches and feedyards for compliance with value-added programs. Their PVP programs include standard USDA programs like age and source verified and natural (not treated with any hormones or antibiotics). BeefChain also has a program that identifies and tracks calves born on Wyoming grazing lands through an integrated production system. A Wyoming-born calf born can be finished in a feedyard in Washington or Nebraska and remain in the program. BeefChain's goal is to increase the value of cattle for ranchers by providing a digital identity (RFID tag or label) and traceability (blockchain) from the grazing lands to consumers (Pirus, 2019). While blockchain can connect consumers to beef raised on ranches and produced through an integrated production system, it is unclear if consumers will be willing to pay more.

CONCLUSION

Ranchers' decisions to move cattle around and off California's grazing lands are similar to decisions that pastoralists have made for millennia where livestock's needs are matched with variable forage resources. Livestock mobility, which is critical to livestock production and the management of resources on non-equilibrium rangeland systems, is supported by the integration of beef production systems. Ranchers move animals across biomes and pastures, and they move cattle to other production systems, typically to more intensive systems. Intensive production systems, including other grazing land and feedyards, provide feed resources for improving the efficiency of growing and finishing cattle. Integrating the beef production-scape through transportation and trade (saleyards and markets) expands system boundaries beyond local resources, even when non-market-based forms of livestock mobility or expanding the production-scape have been hindered. This integration supports finishing cattle for markets, the maintenance of extensive rangeland, and grazing management.

Extensive rangelands maintained with native and naturalized plants, and managed grazing can support natural diversity, including providing habitat for wildlife. Developing the whole value chain has supported California's ranchers in managing grazing and providing multiple ecosystem services from rangelands, including beef production. Communication and data technologies, like blockchain, may help transfer production information through integrated production systems to improve livestock performance and inform markets and consumers.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Committee for Protection of Human Subjects, University of California Berkeley. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

Concept, research, analysis, and writing were all conducted by SB.

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Management of Grazed Landscapes to Increase Soil Carbon Stocks in Temperate, Dryland Grasslands

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Management of the temperate, grazed grasslands in New Zealand for more than a century has led to swards dominated by ryegrass/clover, which, with inputs of inorganic fertilizers, are highly productive for grazing animals. In the last 20 years the widespread introduction of irrigation to dryland areas on flat land has increased productivity further. However, these intensive practices decrease soil carbon stocks. In contrast, there is limited evidence that improved management of dryland, grazed, hill country grasslands can lead to increases in soil carbon stocks. To address global needs for food security and climate change mitigation, priority actions to increase soil carbon stocks need to focus on improved management practices to increase carbon inputs and retention in soils identified as having high potential for increasing carbon storage. While there are limited data from New Zealand studies, international observations suggest that soil carbon stocks can be increased by enhancing below-ground carbon inputs from plants with deep roots, using swards with diverse species, and moderate grazing rather than harvesting biomass. However, there is less certainty about the processes regulating the formation and decomposition of soil organic matter and their dependence on soil physical properties and microbial access. Scaling findings from plot studies to forecast long-term changes in soil carbon stocks at the landscape scale can be done using models but new approaches are required to integrate the impacts of multiple concurrent practices associated with grazing management.

Keywords: diverse swards, grasslands, grazing management, microbial processes, soil carbon

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INTRODUCTION

Grasslands occupy 26% of the global land area (Conant et al., 2017) and their use for grazing livestock across 34 million km^2 provides a critical contribution to food security to meet the demands of an increasing global population (Soussana et al., 2010). Because of the extensive area of grasslands, the carbon stored as soil organic matter (SOM) amounts to 20% of global carbon stocks to a depth of 1 m (Stockmann et al., 2013). Improved management of grasslands to increase carbon stocks (McSherry and Ritchie, 2013; Conant et al., 2017) could help mitigate agricultural greenhouse gas emissions (Smith et al., 2016), improve soil fertility (Lal, 2004), and enhance the resilience of agricultural systems to extreme weather events (Pan et al., 2009). Zomer et al. (2017) estimated that global cropland soils could sequester 26–53% of the target carbon storage of the 4 per 1,000 Initiative (Soussana et al., 2017). However, predicting the impacts of management on grassland soil stocks is problematic because of the complex interactions among climate and soil types (Conant et al., 2017), and management practices including grazing intensity, frequency, and duration (Zhou et al., 2017), irrigation, fertilizer addition, and plant species mixes. Grazing animals decouple the stoichiometric linkages between carbon and nitrogen cycling in soils by the removal of biomass and return of carbon in dung and high concentrations of nitrogen in urine patches (Soussana and Lemaire, 2014).

The focus of this perspective is on temperate grasslands in New Zealand, where 55% of the land area is managed for sheep, beef and dairy cattle, but agricultural production also contributes 50% of national greenhouse gas emissions (Whitehead et al., 2018). Average soil carbon stocks are moderately high (Tate et al., 2005), and maintaining these stocks is important because further increases are likely to be difficult to achieve (Minasny et al., 2017). Much of the focus on changes in carbon stocks in New Zealand has been on flat, highly productive sites used for dairy farming (Schipper et al., 2017; Whitehead et al., 2018), where there is increasing concern that mean soil carbon stocks at sites irrigated for 3–90 years were 6.99 tC ha^{-1} lower than those at adjacent non-irrigated sites (Mudge et al., 2016).

In contrast, there is evidence from two studies that carbon stocks (0.3 m depth) increased on managed, non-irrigated hill country with a slope of about 30% at about 1.3 tC ha^{-1} y^{-1} over 5 years (Parfitt et al., 2014) and about 0.6 tC ha^{-1} y^{-1} over 30 years (Schipper et al., 2014). These findings are highly uncertain because of possible sampling anomalies, but may be attributable, in part, to the re-formation of topsoil following the historical removal of trees and increased nitrogen availability from fixation by leguminous clover species (Parfitt et al., 2013). This suggests that introducing forage legumes into New Zealand's extensive hill country grasslands (Monk et al., 2016) could increase carbon stocks at low cost (Vermeulen et al., 2019), with additional environmental and social benefits (Smith et al., 2016).

PROCESSES REGULATING CHANGES IN SOIL CARBON STOCKS

There is an underlying assumption that increased photosynthesis and above-ground biomass will increase carbon inputs and retention as SOM. However, increases in primary production often result in increased removal of biomass by grazing or cutting (Mackay et al., 2018). Further, biomass removal, plant composition of swards, compensatory growth, biomass decomposition, and carbon return in animal excreta all affect SOM formation and decomposition. So, increased carbon inputs may lead to small changes, no changes, or even losses in carbon stocks.

To investigate the effects of interacting management practices on soil carbon, Kirschbaum et al. (2017) identified four key points of constraint that regulate the transfer of carbon inputs into stabilized SOM: (1) carbon inputs, (2) biomass export by grazing or cutting, the effects of changes in the amounts and chemical nature of carbon inputs on (3) retention into different pools for SOM formation, and (4) carbon loss from SOM decomposition (**Figure 1**).

The allocation of carbon below-ground depends on vegetation type and growing conditions but, from a review of 128 studies, Pausch and Kuzyakov (2018) estimated that grasses allocated 33% of carbon fixed by photosynthesis below ground, of which 16% was stored in roots, 12% lost as root respiration, and 5% deposited as root exudates in the rhizosphere (constraint 1). Using a ^{14}C tracer over 35 days, Saggar et al. (1997) showed that the proportion of carbon allocated to roots was 10% higher for a low-fertility grassland than that for a high-fertility grassland, but the total amount of carbon allocated was higher for the high-fertility grassland. Carbon inputs from plant material as litterfall and from root death are also variable. However, inputs from above-ground biomass can be reduced by 60% when biomass is removed by grazing or cutting (constraint 2) (Soussana et al., 2010). Of the biomass intake by cattle, 25–40% as non-digestible carbon is returned to the soil in dung (Soussana et al., 2010), resulting in decoupling of the carbon and nitrogen cycles (Soussana and Lemaire, 2014). Processing by soil fauna and microbes partitions carbon inputs into pools that can be labile and lost, or into more stable carbon compounds that are retained to form SOM (constraint 3), or are decomposed (constraint 4).

INCREASING PLANT CARBON INPUTS TO SOIL

Swards of perennial ryegrass (*Lolium perenne* L.) with nitrogen-fixing white clover (*Trifolium repens* L.) are dominant in New Zealand grassland systems because they are productive and managed easily for rotational grazing (Crush et al., 2005). However, intensive breeding programmes have favored above-ground biomass production at the expense of carbon allocation below-ground (Lee et al., 2012). Plants with deep roots and high root biomass may increase soil carbon inputs (constraint 1), but this may be tempered by a trade-off with reduced carbon allocation above-ground and differences in root longevity. However, swards with high species diversity comprising grasses, legumes and broadleaved forbes (Kell, 2011; Mueller et al., 2013) can be more productive, more resilient to periods of drought, and lead to increased SOM storage (Nobilly et al., 2013; Lange et al., 2015). This is attributed to the combination of plant traits (Wright et al., 2004) that enhance the use of resources to avoid inter-species competition (Mason et al., 2016). McNally et al. (2015) estimated that increased root mass and rooting depth for a sward with seven species compared with conventional ryegrass/clover could increase soil carbon inputs to a depth of 0.3 m by up to 1.2 tC ha^{-1}. Rutledge et al. (2017a) estimated net carbon balance at the same site for 3 years following conversion to both the mixed and conventional swards. Accounting for differences between the two sites prior to conversion, net carbon gain by the mixed sward occurred more rapidly and was 2.5 tC ha^{-1} higher over 3 years than that for the conventional sward.

Renewal of grassland swards by re-seeding with new cultivars is common practice to enhance productivity, although this is usually confined to flat land with high-intensity grazing (Kerr

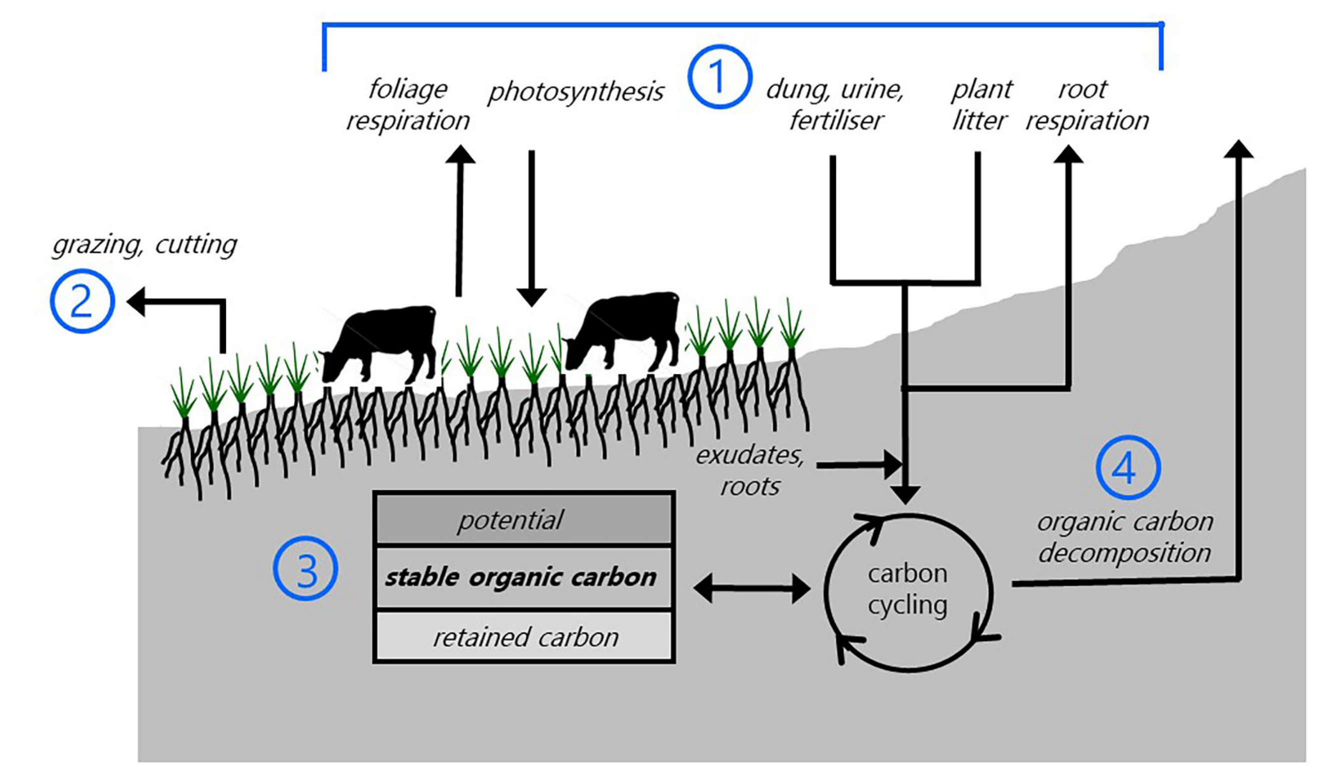

FIGURE 1 | Conceptual diagram of the components of carbon balance and the four key points of constraint that regulate the transfer of carbon inputs into stabilized soil carbon in a grazed system: (1) carbon inputs, (2) biomass export by grazing or cutting, (3) carbon retention as stabilized organic compounds to form soil organic matter, and (4) decomposition of soil organic matter to release carbon.

et al., 2015). Liáng et al. (2020) used a model to show that renewal every 25 years could result in annual carbon losses of 0.16 tC ha^{-1} y^{-1}, but the magnitude depended on plant age effects on the balance of photosynthesis to respiration. Rutledge et al. (2017b) estimated changes in carbon stocks with sward renewal using minimal tillage and showed that losses of soil carbon of 1.6–2 tC ha^{-1} y^{-1} could be minimized by reducing the length of the fallow period, sowing in conditions favorable for rapid establishment, and adding supplementary carbon inputs. Paddock-scale measurements over 10 years with variable weather conditions in Switzerland also highlighted the need to minimize fallow periods following sward renewal to avoid carbon losses (Ammann et al., 2020).

In a meta-analysis of global data from 192 studies, Conant et al. (2017) showed that fertilizer addition, increased species diversity (including legumes), irrigation, and reduced cultivation increase soil carbon stocks of between 0.1 and 1.0 tC ha^{-1} y^{-1}, but the positive effects were specific for climate, soil type, and vegetation characteristics. Large increases in productivity resulting from variable-rate applications of fertilizers in New Zealand hill country depend on soil type and slope (White et al., 2017). However, the effects on carbon stocks are not clear because there are, surprisingly, few field measurements of the effects of nutrient availability on production, the allocation of carbon below-ground, and carbon stocks (Whitehead et al., 2018). Schipper et al. (2017) concluded that application of phosphorus to four flat and hill country sites over 24–60 years showed no changes in carbon stocks. Application of lime to hill country is a common practice to increase soil pH and improve productivity. Findings from long-term studies of grasslands in France suggest that adding lime increases rates of SOM decomposition, but the magnitude depends on the effects of nitrogen management on the soil microbial community (Lochon et al., 2018). Measurements over 129 years from the Park Grass experiment in the UK also showed that adding lime increased SOM decomposition rates, but this was offset by increased incorporation of carbon inputs into stabilized carbon pools (Fornara et al., 2010).

IMPACTS OF GRAZING MANAGEMENT PRACTICES

The frequency and intensity of biomass removal by cutting or grazing and the return of carbon and nitrogen as dung and urine (constraint 2) regulate soil carbon inputs (Soussana et al., 2010). Although foliage removal by grazing reduces photosynthesis (Giltrap et al., 2020) and possibly carbon inputs to soil (McSherry and Ritchie, 2013), post-grazing plant growth can be stimulated. Further, this may increase the proportions of unpalatable broad-leaved species relative to grasses (Abdalla et al., 2018), which could also increase carbon inputs. Analysis of changes in grassland soil carbon stocks in relation to climate zones revealed strong interactive effects of grazing intensity, temperature, and precipitation (Abdalla et al., 2018).

Findings from paired comparisons of grazing treatments show conflicting results. In northern China, intensive grazing resulted in a decrease in carbon stocks that was reversed by animal exclusion over 30 years (Wang et al., 2011). Chen et al. (2015) showed that carbon stocks at low and high grazing intensities were lower than those at moderate grazing intensity in the Steppe region in China. In New Zealand there were no differences in carbon stocks for grassland grazed at different intensities by sheep on hill country (Hoogendoorn et al., 2016). After removing the interactive effects of climate, Sanderman et al. (2015) attributed 22% of the variability in carbon stocks to differences in grazing management in southern Australia but they were unable to detect significant differences between continuous and rotational grazing practices. Bork et al. (2020) showed that the variability in soil carbon stocks across 32 sites in a Canadian prairie was explained more by livestock numbers than rainfall. Orgill et al. (2018) compared carbon stocks in ungrazed, continuous grazing with bi-annual rest periods and intensive grazing with frequent rest periods after 5 years, all well-supplied with nutrients, in southern Australia. Carbon stocks were 28% higher in the intensive grazing treatment compared with the ungrazed treatment, suggesting that increasing grazing intensity may lead to short-term increases in carbon stocks. The effects were attributed to differences in carbon allocation to roots and shoots, root growth rates and turnover, shading effects, and nutrient availability. Franzluebbers et al. (2019) were not able to detect differences in carbon stocks after 8 years of continuous and rotational grazing in tallgrass prairie in North America.

In European grasslands, both grazing and mowing are common management practices (Soussana et al., 2010). At adjacent grassland sites in central France, net carbon uptake from photosynthesis was higher when paddocks were mowed than grazed (Puche et al., 2019). However, accounting for biomass harvest reduced net carbon gain for the mowed sites. Koncz et al. (2017) showed that soil respiration for a dryland grassland in Hungary over a 3-year period was 20% higher for mowing compared with grazing and attributed this to differences in above-ground biomass with minor effects from seasonal changes in soil water content and temperature. Oates and Jackson (2014) concluded that the dominant components determining annual carbon balance in grazed grassland in northern central USA were cool-season carbon inputs from photosynthesis and losses from soil respiration.

RETENTION AND STABILIZATION OF SOIL CARBON

The processes regulating carbon retention and the formation (constraint 3) and decomposition of stabilized SOM (constraint 4) depend on interactions among the composition of carbon inputs, soil texture, and microbial communities. The protection of carbon as relatively simple organic products from microbial decomposition is associated with organo-mineral complexes (Basile-Doelsch et al., 2020; Lavallee et al., 2020). Management can disrupt these processes, but the complexities are not well-understood (Dignac et al., 2017).

The concept of carbon saturation for individual soils is contentious (Chenu et al., 2018), but the capacity of soils to store carbon is strongly related to the availability of stabilization surfaces in the mineral matrix. This can be estimated from the specific surface area of the soil particles (Beare et al., 2014; McNally et al., 2017), calculated from the adsorbed water content after air drying in controlled conditions (Kirschbaum et al., 2020a). In a conceptual model, Kirschbaum et al. (2020b) showed that the amount of protected SOM is strongly related to the rate of carbon input, the soil specific surface area, and the rate of SOM turnover regulated by climate, soil texture, and environmental variables. The model showed that there is no upper limit to the protected SOM.

Using ^{13}C labeling with ryegrass and clover growing in mesocosms, Carmona et al. (2020) showed that irrigation increased above-ground biomass and the amount of carbon partitioned into above-ground biomass by 16%, but decreased the proportion partitioned to roots by 35% compared with non-irrigated plants. However, irrigation did not increase the quantity of net carbon inputs to the soil. The findings suggest that soil carbon losses with irrigation could be explained by increased turnover of root-derived carbon rather than reduced carbon inputs and/or by the effects of changes in the composition of carbon inputs on decomposition. Crème et al. (2017) reported that changes in the chemical composition of litter and root tissue when nitrogen-fixing lucerne was introduced into grassland increased SOM decomposition more than SOM stabilization.

The effects of fertilizer application, sward diversity, grazing, and dung deposition on carbon transfer, stabilization, and decomposition are regulated by microbial processes. Findings from the addition of lime to grassland by Fornara et al. (2010) and Lochon et al. (2018) were consistent with the increase in pH resulting in a change in microbial community composition and increased microbial activity leading to increased SOM decomposition. The long-term Jena Experiment showed that greater soil carbon storage with higher plant diversity was attributable to increases in rhizosphere carbon inputs to the microbial community with small effects on SOM decomposition (Lange et al., 2015). Zhao et al. (2017) used meta-analysis to show that light and moderate grazing intensity had no effect on microbial communities. In contrast, heavy grazing resulted in losses of bacterial and fungal communities, but an increase in the ratio of fungal to bacterial communities that may have decreased rates of nutrient turnover. In comparison with an unmanaged control, Gavrichkova et al. (2008) showed that the combined effects of mowing and grazing enhanced rhizodeposition and the availability of carbon substrates for microbes, but decreased rates of SOM mineralisation, suggesting that the microbial community became more energy efficient.

CONCLUSIONS

Several knowledge gaps persist as barriers to identify management practices to increase soil carbon stocks. They include a lack of data from field measurements of the interacting effects of climate, soil, and management practices on microbial communities and below-ground processes, slow rates of change and high spatial variability in soil carbon stocks in field conditions (Whitehead et al., 2018). Increases in uncertainty in measuring changes in stocks with increasing spatial scale (Maillard et al., 2017) and the consequences for other ecosystem services deter adoption of practices by farmers and policy makers (Bradford et al., 2019).

Three approaches are needed to reveal insights into increasing carbon stocks: (1) increased field measurements to reduce uncertainty in the effects of management, including management history, on soil carbon stocks, (2) meta-analysis of long-term (decades) field observations, and (3) detailed short-term (months), often small-scale, experimental observations in laboratory conditions. A fourth approach, modeling to integrate concepts and observations across spatial and temporal scales, will provide the capability to forecast the impacts of interacting management practices on soil carbon stocks (Wang et al., 2020). For dairy farming, Kirschbaum et al. (2017) used a model to demonstrate that the complexity of multiple drivers can lead to feedback responses resulting in trade-off effects on outcomes other than carbon stocks, specifically meat and milk production. A similar analysis is yet to be done for extensive grazing regimes on dryland hill country.

From the processes regulating the points of constraint on carbon flows identified in **Figure 1**, the major effort has been to identify management interventions to increase soil carbon inputs. Moderate grazing, dung returns, introducing legumes (Soussana et al., 2010; Monk et al., 2016), increasing sward diversity (Lange et al., 2015), rotational grazing (Oates and Jackson, 2014) and lower grazing or cutting intensity (Koncz et al., 2017) can minimize carbon losses, maintain carbon stocks and mitigate greenhouse gas emissions. However, further research (Whitehead et al., 2018) is needed to determine the impacts of management practices on the below-ground processes that influence the formation and decomposition of SOM and carbon stocks, independent of carbon inputs.

Integrating the findings from plot studies, usually limited to investigating a few variables, to include complex interactions from multiple simultaneous management practices and scaling to landscapes including hill country, are problematic, but initial attempts using models are promising (Wang et al., 2020). Identifying management practices that increase carbon inputs, retention and SOM formation, and reduced decomposition, especially on soils with a high potential to store carbon (McNally et al., 2017; Kirschbaum et al., 2020a), could provide a useful framework for managers to increase carbon stocks at landscape scales.

AUTHOR CONTRIBUTIONS

DW developed the ideas and wrote the manuscript.

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frontiers in Sustainable Food Systems

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Toward Specialized or Integrated Systems in Northwest Europe: On-Farm Eco-Efficiency of Dairy Farming in Germany

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Intensive confinement (IC) systems for dairying have become widespread during the last decades. However, potential advantages of alternative systems such as full-grazing (FG) or integrated dairy/cash-crop (IFG) systems with regards to better provision of ecosystem services are widely discussed. To investigate performance and environmental impacts, we compared four prevailing dairy systems using an on-farm research study. The farm types differed in their share of pasture access and quantity of resource inputs: (i) an IC with a high import of supplements and mineral fertilizers; (ii) a semi-confinement (SC) with daytime pasture access during summer and moderate import of supplementary feeds representing the base-line scenario; (iii) a FG based on grazed seeded grass-clover swards with no purchased N-fertilizers and low quantities of supplementary feeds; and (iv) an IFG comparable to FG but based on grass-clover leys integrated in a cash-crop rotation. Results revealed highest milk productivity (16 t energy-corrected-milk (ECM) ha^{-1}) and farm-N-balance (230 kg N ha^{-1}) in IC; however, the highest product carbon footprint (PCF; 1.2 CO_2eq kg ECM^{-1}) and highest N-footprint (13 g N kg ECM^{-1}) were found in the baseline system SC. The FG and IFG revealed on average similar forage dry matter yields (10 – 11 t DM ha^{-1}) at similar crude protein and net-energy-lactation ratios per kg DM-intake compared to the IC and SC. The PCF in FG were comparable to IC (0.9 vs. 1.1 kg CO_2eq kg ECM^{-1}) but at a lower N-footprint (9 vs. 12 g N kg ECM^{-1}). However, despite low measured N-losses in the FG system, the farm-N-surplus was exceeded by 90 kg N ha^{-1}. A further reduction was only possible in the IFG (50 kg N ha^{-1}) by accounting for a potential N-carry-over from N-rich plant residues to the cash-crop unit, leading to the lowest PCF (0.6 kg CO_2eq kg ECM^{-1}) for the IFG, with still moderate milk yield levels (∼10,500 kg ECM ha^{-1}). According to this bottom-up approach based on field data, improved integrated grazing systems could provide an important opportunity to increase the ecosystem services from dairy farming, operating with land use efficiencies similar to IC.

Keywords: forage-productivity, rotational-grazing, PCF, soil-carbon-storage, farm-N-balance, ley farming, dairy cows

INTRODUCTION

Ongoing intensification in agriculture has led in many developed countries worldwide to highly specialized dairy production systems, with declining numbers of farms, larger herd sizes, and increasing milk yields per hectare (Peyraud et al., 2014). In recent years, the spatial distribution of dairy farms has continued to shift into areas with lower land prices and unsuitable conditions for arable crop production, or regions that continue to specialize on animal husbandry due to the poor competition with other cash crop producers on the global market. For instance, in the European Union (EU) half of the livestock units are located on one-third of the agricultural area (Leterme et al., 2019). In the South Island Regions of New Zealand, where historically there were significant shares of oat and wheat production together with animal husbandry, the arable area for cash-crop production declined by 80%; at the same time the stocking rates increased by 150%. This was enabled by converting rain fed to irrigated grassland systems, which are now mainly used for dairying (Ledgard, 2013). As a result, the diversity of agricultural commodities produced on farms in these areas declined and undesired environmental impacts increased, including increases in nitrate concentrations in drinking water (Vogeler et al., 2014), and in ammonia (NH_3) volatilization (Fowler et al., 2013), as well as loss of plant, insect and bird species diversity (Kleijn et al., 2009; Ledgard, 2013; Allan et al., 2014), and a decline in natural forest (Ledgard, 2013).

The concept of sustainable intensification has evolved as a response to the environmental challenges associated with agriculture (Davies et al., 2009) and has been a topic of interest in recent years (Garnett et al., 2013; Barnes et al., 2016; Reheul et al., 2017; Struik and Kuyper, 2017). Sustainable intensification involves simultaneously improving the productivity and environmental management of agricultural land (Buckwell, 2014). Closely linked to sustainable intensification is the concept of resource-use efficiency or eco-efficiency (Keating et al., 2010; Taube et al., 2014; Tittonell, 2014; Cook et al., 2015), in which the quantity of resource input, environmental loads, or ecosystem services provided is related to the unit of product (Wilkins, 2008). Ecosystem services can be manifold, however, according to the current common agricultural policy (CAP) of the European union (EU), greenhouse gas (GHG) mitigation and nutrient cycling are of foremost importance in order to tackle the most relevant environmental impact categories (i.e., climate change, eutrophication, biodiversity loss). Critical voices question the applicability of sustainable intensification in Europe by arguing that agricultural systems are already operating at a high production intensity and the concept would be an appropriate strategy for regions characterized by a large yield gap, as for instance in developing countries (Mueller et al., 2012). In regions with highly intensive crop and livestock production, however, sustainable intensification would appear less likely to provide benefits in terms of yield progress when considering the high risk of environmental threats (Garnett et al., 2013; van Grinsven et al., 2015). Some authors are therefore proposing the term "ecological intensification" instead of "sustainable intensification" for use in OECD countries (Godfray and Garnett, 2014). A study by Schiefer et al. (2016), classifying soil biochemical and physical properties as indicators of soil resilience, found only 40% of soils in the European Union (EU-25) to be suitable for sustainable intensification, while on the remaining land de-intensification or conversion from arable to grassland may be warranted. In this context, the term "sustainable extensification" was coined (Bluwstein et al., 2015; van Grinsven et al., 2015).

As one strategy toward ecological intensification, several authors have recommended a paradigm change from highly specialized production systems back to integrated crop livestock systems (ICLS) in order to increase diversity of land use and resource efficiency (Rockström et al., 2009; Godfray and Garnett, 2014). Different levels of ICLS production are currently discussed: (i) integration of crop and animal production by exchanging materials, (ii) complementary exchange of materials with each system taking the production requirements of the cooperatives into account, (iii) temporal and spatial integration on farm-level using fully or partly the same territory, and (iv) the extrapolation of (v) on the regional level (Moraine et al., 2014). A meta-analysis conducted by Peterson et al. (2020) covering data from Australia, North America and South America found that ICLS systems provide higher cash crop yields on fertile sandy loamy soils in comparison to non-integrated systems. This effect was, however, lower, if dual-purpose crops and other soil types were considered. According to Ryschawy et al. (2012) the economic benefit of ICLS depends on the production level and management, as a wide range of management options exists in comparison with more specialized systems. The majority of studies indicated positive environmental effects of ICLS systems (Ryschawy et al., 2012; Moraine et al., 2014; Peterson et al., 2020) due to improved C- and N-cycling among the systems (Lemaire et al., 2015) and consequently a lower demand for external resources. Thus, lower N and phosphate surpluses can be attained. Furthermore, most of the studies found a positive effect on soil organic carbon (SOC) with increased rates of C-sequestration and enhanced soil functioning properties. The latter has mainly been observed when grass or grass-clover was included within the crop rotation (Lemaire et al., 2015; Loges et al., 2018a) often referred to as the ley-phase. The increments of soil C stocks increase with the duration of the ley-phase (Lemaire et al., 2015). For leys, grass-clover swards (usually white clover) are most commonly recommended, as the clover as a forage legume provides additional N through biological nitrogen fixation (BNF). Greenhouse gas emissions, in particular those from the potent GHG nitrous oxide (N_2O), as well as N-leaching losses, are low from grass-clover leys, even though high amounts of BNF (193–319 kg N ha^{-1} $year^{-1}$) can be reached (Høgh-Jensen et al., 2004; Reinsch et al., 2020). This indicates there is an effective N-cycling in such systems (Schmeer et al., 2014; Reinsch et al., 2020). Beyond the mentioned ecosystems services from ley systems, there are additional questions on biodiversity that can be addressed with multispecies swards at low rates of mineral N are used. For instance, Ebeling et al. (2008) found a linear trend for pollinator visits with increasing numbers of flowering plant species. Moreover, the introduction of leys in arable-cropping systems reduces the pressure of undesired weeds (Connolly et al., 2018; MacLaren et al., 2019) and consequently the use of agrochemicals, which may thereby allow a further increases in the biodiversity of agricultural land (Holzschuh et al., 2007). However, even greater biodiversity increase can be expected by increasing crop diversity and from the increased landscape heterogeneity of integrated crop livestock systems (Sirami et al., 2019).

Research on alternative production systems for dairying in northwest Europe currently attracts a lot of attention from policy makers and from society in general, because of the environmental effects of mainstream intensive systems as well as the questionable economic performance of dairying since the abolition of the milk quota system. Moreover, producers are facing the challenge on how to re-direct their systems in order to reach the multidisciplinary aims (e.g., compliance with EU-Nitrate Directive, EU-Water Framework Directive, EU-NEC Directive) and to be in line with the EU climate target plan (Green deal) to become climate friendly by 2050 (EC, 2020). Nowadays, dairy husbandry in northwest Europe is the second largest sector in terms of output value from agriculture (Augère-Granier, 2018). The average stocking rate in the intensive dairy producing countries (Netherlands, Germany and Denmark) is $>$1.4 LU per ha of UAA (Eurostat, 2018), and average milk yields per cow are 9,247 litre per year (Eurostat, 2020). To maintain high milk yields per ha for the market, silage production and intensive supplementary feeding has increased in the last decades, at the cost of grazing and low-cost feeding (Taube et al., 2014). Additionally, high amounts of mineral fertilizers are purchased to maintain high forage yields and yield stability, despite high amounts of organic manures being available. Consequently, the total amounts of nutrient supplies from organic manures and purchased fertilizers on dairy farms often exceed the demand requirements for on-farm forage production, particularly from seasonal surpluses of manure. This necessitates a high share of exportation of manures to cash crop producers (Oenema et al., 2014). The N in animal manures also has a high potential for gaseous N-emissions, during both storage and application depending on time and technique used (Misselbrook et al., 2000). The farm-N surplus can exceed 200 kg N ha^{-1} $year^{-1}$ particularly if there is substantial supplementary feeding (Akert et al., 2020). van Grinsven et al. (2013) calculated a range of social costs from the impact of reactive N on human health, ecosystems and climate of 10–30, 5–20, and 4–17 € per each kg N emitted in the EU-27 states. As one of the consequences, the European Nitrates Directive restricts the total amount of manure N to 170 kg ha^{-1} $year^{-1}$ and ban slurry application from autumn and winter in order to reduce the N-pollution of groundwater bodies. This, in combination with the current spatial distribution of highly specialized systems, has led to logistic challenges, with long transport distances for manures, long manure storage durations, and high capacity manure storage facilities needed (Kuhn et al., 2018). This handling of manures increases the potential for NH_3 volatilization, which decreases the N-use efficiency (NUE) of dairy farms to below 30% (Löw et al., 2020). Alternative solutions for dairy farms to use adapted forage crops, such as legumes, are limited as they provide additional N. This biologically fixed N has to be included in fertilizer planning and, as a consequence, more N has to be exported. In addition, farmers are often concerned that considerable yield losses could occur after the adoption of forage legumes, even though several studies have confirmed an effective N-fertilizer replacement value across a wide range of legume-based ley-mixtures (Suter et al., 2015). This, and the high inter-annual yield resilience under current and future climate change make such legume-based ley mixtures even more attractive (Lorenz et al., 2020).

Within the hierarchy of current developments in the dairy sector, there are discussions about whether a trend back to pasture-based production systems would contribute to reduced environmental impacts and more resilient farming systems in northwest Europe (Schils et al., 2019). The revenue of a dairy farm depends on the market price for milk, and the share of home-grown feed and use of external resources, like supplements. Several studies have revealed that the lowest costs per unit dry-matter intake (DM-intake) can be obtained through low-cost full-grazing strategies ensuring grazing almost year-round at a low share of supplementary feeding, as is common in Ireland, Australia and New Zealand. Such grazing strategies are best suited in regions with adequate rainfall and fertile soils, as found in parts of the Netherlands, northwest Germany and Denmark. The lowest feeding cost per liter of milk unit can be generated by a high home-grown forage use efficiency and low rates of supplementary feeding (Dillon et al., 2008). This can be achieved through a high frequency of short grazing intervals (i.e., rotational grazing), as this ensures that forage is offered with high energy and protein contents. Further improvements can be gained by including forage legumes in grass-clover swards, as this reduces costs further, and also can reduce GHG emissions (Li et al., 2011; Nyameasem et al., 2021). In comparison with confinement systems, these low-cost full-grazing strategies need adjustments in the choice of the animal breeds and calving interval. High yielding Holsteins often cannot realize a sufficient dry matter intake under grazing conditions and might be sensitive to variations in the herbage on offer and weather conditions (Heublein et al., 2017). Smaller cows, such as cross-breeds and Jerseys, are often judged as better grazers. Optimal grazing efficiency is often reached by synchronization of high (spring) pasture growth with the peak of lactation. To achieve this, seasonal spring calving with short calving intervals is the predominant calving pattern in pasture-based milk production.

However, such management results in lower productivity per animal, as well as per hectare of farmland as long as "imported land" is not included. This makes the overall environmental efficiency questionable, as it is often highlighted that high milk yields per cow result in a lower product carbon footprint (PCF). A negative relationship between the PCF and milk yield was found in a variety of studies (Christie et al., 2012; O'Brien et al., 2014; Zehetmeier et al., 2014). For example, Christie et al. (2012) explained 64% of the variation of the PCF by milk yield per cow, and Zehetmeier et al. (2014) explained 55% (Holstein Friesian cows) and 30% (Fleckvieh cows) of the milk PCF by the production system. Gerber et al. (2011) found that at energy corrected milk (ECM) yields below 2,000 kg per cow and year, an increase of milk yield provides a strong reduction of emissions per unit product, while above 6,000 kg the emissions stabilize. While the total energy requirement per cow increases with an

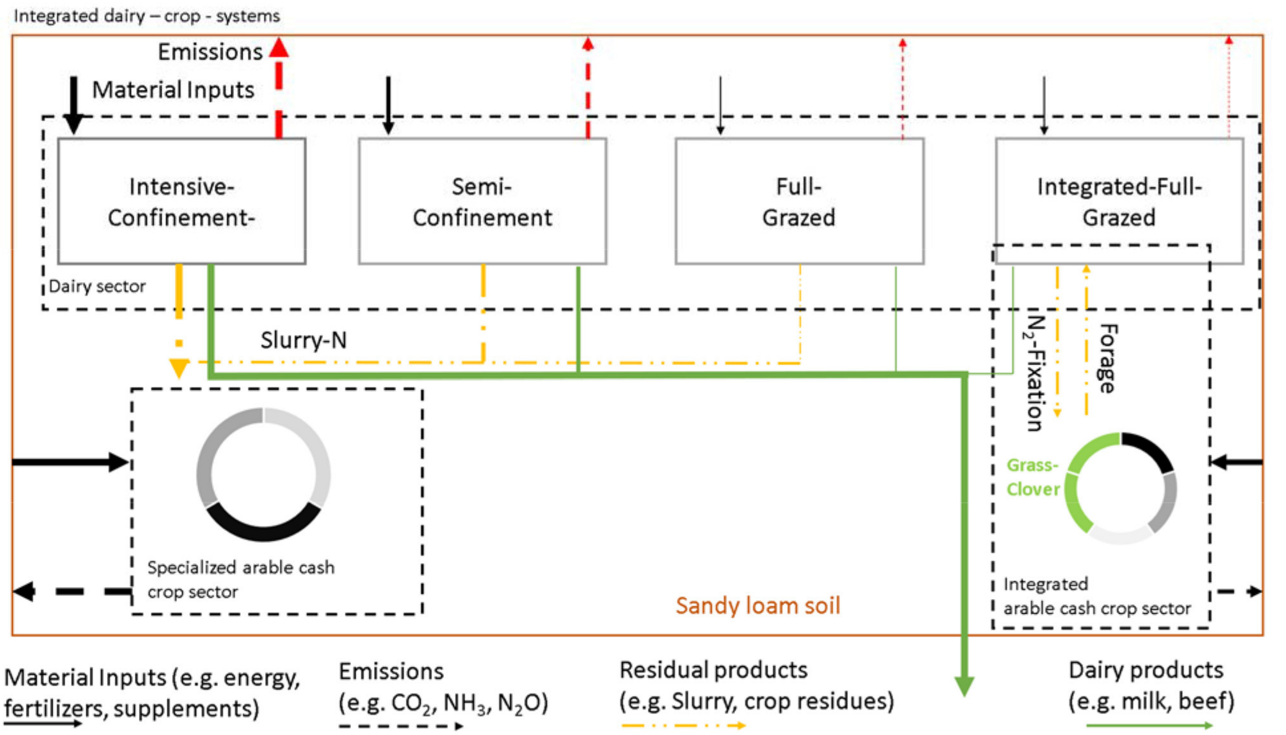


FIGURE 1 | Assumption of input and emission flows within the prevailing dairy systems. The system boundaries indicate the scope of the conducted farm evaluation.

increase in milk yield, the amount required for maintenance remains unchanged. This results in a decline of the proportion of total energy used for maintenance and the total energy requirement per kg of milk produced (Capper et al., 2009) in a ceteris paribus scenario (e.g., same number of lactations per cow). However, since it is very likely that higher milk performance per cow coincides with a reduced number of lactations, optimum levels of PCF do not increase linearly with milk performance. Considering more intensive systems with milk yields >5,000 kg energy corrected milk (ECM) per cow and year, Lorenz et al. (2019) found in a meta-analysis that low-cost full grazing systems show no disadvantages in the PCF in comparison with intensive confinement systems.

The suitability of ICLS systems for dairy production has, so far, been poorly evaluated on a regional level without taking high production intensity, such as for dairying in northwest Europe, into account. The insertion of leys into the crop rotation will also provide benefits for cash crop producers (e.g., nutrient provision, soil water retention, and control of pests) and also help ensure mutual outputs such as climate regulation and biodiversity, regardless of whether the ley is used for silage production, cut and carry, or grazing (Martin et al., 2020). However, where soil conditions allow grazing as a low resource-use practice the ley-phase should be sought to reach the maximum potential of ICLS.

Thus, as part of the debate on the development of more sustainable dairy systems within the frame of ecological intensification approaches that ensure appropriate production levels on the one hand, and additional ecosystem services on the other, four model scenarios along the hierarchy of current and possible systems in northwest Europe can be defined: intensive-confinement (IC), semi-confinement (SC) with a limited grazing period, full-grazing systems (FG) conducted on seeded permanent grassland, and an integrated full grazing system (IFG) predominately conducted on leys (**Figure 1**). In accordance with the meta-analysis from Lorenz et al. (2019) the thresholds between IC, SC, and FG systems are set by the forage intake from pasture. In the IC systems animals have no allowance for pasture, while in SC <50% of the feed intake is from pastures and a minimum 25% is from supplementary feeding, whereas in FG and IFG systems a minimum 50% of feed intake is from pastures with a maximum share of 25% from supplements. The main advantages of an IFG is the possibility of the inclusion of leys in a cash-crop arable system to accelerate C and N accumulation in the soil as a result of BNF from grass-clover leys and animal-N excreta; and in terms of forage provision the benefits of continuous progress in forage plant breeding, as expressed as high energy and protein values similar to concentrate feed, can be gained by frequent renovation of the seeded leys. Moreover, leys offer the opportunity to include alternative species such as forage herbs that may benefit the digestibility and forage intake of grazing animals (Loza et al., 2021) at low N_2O emissions from pasture land (Nyameasem et al., 2021).

Lorenz et al. (2019), moreover, noticed that the efficiency of the proposed dairy systems depends on the farm management and that the evaluation of such systems needs accurate estimates of the forage efficiency. Accordingly, we decided to choose a set of representative farms together with the regional commercial dairy extension service, which fulfilled the above-mentioned thresholds of feed allowance, and to investigate them over 2 years using a bottom-up approach. Even though on-farm research approaches often lack the statistical accuracy provided in a randomized experimental design, they offer valuable insights into practical management approaches, which may be shown to be economical resilient over successive years. Moreover, to gain a representative picture on the effects on C- and N-cycles, systems have to be established over years before the long-term impacts can be investigated. This situation is difficult to duplicate in randomized plot experiments for dairy systems, as (i) dairy cattle have a large requirement for land, especially if fundamentally different production systems are compared, and (ii) long-term investigation would be necessary in order to take account of altered chemical soil properties that occur as a result of the management. Thus, all farms in our study had already been established for several years and were located on the same soil type. Productivity and environmental impacts such GHG-emissions and N-leaching from forage crop production were measured for two years and the PCF, NH_3, and farm N-balance were calculated. The following hypotheses have been made:

- Increasing intensification in dairy causes higher emissions and high N-surpluses per ha and per kg of milk in comparison with semi-intensive systems that include grazing.
- Full grazing is more advantageous in terms of the mentioned ecosystem services, in particular low-cost systems without high use of external resources.
- The latter can be further improved by ICLS.

MATERIALS AND METHODS

Research Area

The study was conducted in the eastern part of Schleswig-Holstein, northern Germany. The soil type in this region is predominantly sandy loam, and highly suitable for arable production with high yields of both cereals and forages (Loges et al., 2018a; Struck et al., 2019; Biernat et al., 2020b; Reinsch et al., 2020). Among the federal states of Germany, Schleswig-Holstein has the highest stocking density of dairy cattle (at 69 per km^2; compared to average of 27 per km^2) which may be attributed to its climate being well–suited to forage production. Moreover, farming practices are highly specialized toward either cash-crop production or dairying, with low interaction among these systems. This specialization results in high farm-N surpluses and high nitrate loads to the groundwater, particularly in areas where the highest numbers of dairy stock are located (Taube et al., 2015; Biernat et al., 2020). The region has a maritime climate with moderate long-term average temperatures of 8.9°C and annual rainfall of 737 mm. From the 1970s to 2019 the number of dairy farms in the region dropped from 8,000 to below 4,000 (Destatis, 2017). During the same period, the average milk yield per cow has increased from ∼6.000 to ∼9.000 kg ECM, with high variability in milk yields depending on system and specialization. Nowadays, most cows in the region are kept inside year-round, receiving together with grass, maize-silage (at 6 kg DM cow^{-1} day^{-1}) and additional high inputs of supplementary concentrate feed (2.7 t DM cow^{-1} year^{-1}) (LKSH, 2019). The average herd size is 150 cows and average annual milk yield is 8 920 kg ECM per cow. Access to full-pasture land is low as a proportion of the total number of dairy cows (<9%). Within this region and yield levels, we identified four prevailing farm types: (i) intensive-confinement (IC), (ii) semi-confinement (SC), (iii) full-grazed (FG), and (iv) integrated-full-grazed (IFG), with a gradient in the share of grazing and resource inputs (**Table 1**). The SC farm type represents the average production conditions in this region, and its production data are comparable to data from officially published farm surveys. The annual released farm survey data cover 430 representative farms across the country (LKSH, 2019). In SC the animals had, in addition to grass and maize silage, access to pasture during daytime from May-September on the

TABLE 1 | Overview of the prevailing dairy production systems available in the case-study-area as average of two experimental years.

Parameter	Farm type			
	IC	**SC**	**FG**	**IFG**
Full-name	**Intensive-confinement**	**Semi-confinement**	**Full-grazed**	**Integrated-full-grazed**
Location	54°40'N 10°05'E	54°22'N 10°16'E	54°43'N 9°43'E	54°27'N, 9°57'E
Grazing (days year^{-1})	0	80	256	292
Farm area (ha)	67	58	29	56
Share permanent grassland (%)	37 PG	36 PG	51 PGC	17 PGC
Arable forage production (ha)	11 AG 31 SM	14 AG 8 SM 15 RC	11 AGC[a]	46 AGC
Number of dairy cows	95	71	36	85
Breed	HF[c]	HF	Cross-Breed	Jersey
Live weight (kg)	650	650	540	450
Replacement rate (%)	21	35	25	23
Stocking rate (LU[b] ha^{-1} forage area)	1.8	1.6	1.3	1.4
Calving Interval (days)	400 (year round)	395 (year round)	365 (spring calving)	365 (spring calving)
Supplements (t cow^{-1} year^{-1})	3.1	2.4	0.2	0.9
Milk yield (kg ECM cow^{-1} year^{-1})	11,152	9,484	6,060	6,867
Milk fat (%)	3.9	4.2	4.5	5.6
Milk protein (%)	3.3	3.4	3.4	4.0

The different proportions of forage production are shown (PG, permanent grassland; AG, arable grass; RC, red-clover-grass; AGC, arable grass-clover; SM, silage maize; PGC, permanent grass-clover; AGC, arable grass-clover).

[a] *Grazing of catch-crops by heifers were performed on ∼4 ha a^{-1} prior to re-seeding of grass-clover swards in spring.*

[b] *One livestock unit (LU) refers to 500 kg liveweight.*

[c] *Holstein-Friesian.*

land surrounding the cowshed. The IC system was chosen from the top 64 farms in this area according to the milk yield records ($>$10,000 kg ECM cow^{-1} year^{-1}). The cows were confined year-round. Forage in IC was provided from grass and maize silage only. The FG and IFG systems were identified on the same soil type and these systems are not commonly practiced in this region. Thus, these farms acted as an alternative in comparison with the business-as-usual scenarios (IC and SC). The proposed grazing management conducted in FG and IFG followed the principles of rotational grazing adopted from systems as used in Ireland and New Zealand. For instance, the farm manager of FG was part of an international knowledge transfer network working on improved rotational grazing management. The IFG collaborated intensively with the Irish research center Teagasc (Loges et al., 2018b). Both the FG and IFG implemented rotational grazing on diverse grass-clover swards. Stocking rates for dairy cows on pastures in the FG and IFG were adjusted in accordance with non-destructive aboveground biomass measurements (AGB) obtained with a yield-plate-meter (Trott et al., 2002) to ensure an optimal forage allowance. The access to pasture ranged from 0 to 292 days year^{-1} among the systems. The N application from mineral fertilizer and slurry was on average 247 (IC) and 182 kg N ha^{-1} (SC). In FG and IFG the N-fertilization was provided by BNF and N-excreta from grazing animals. The farms IC, SC, and FG were exclusively specialized on dairy and forage production, whereas IFG was part of an ICLS. In detail, forage was offered as grazed grass-clover leys. These leys were plowed after two full grazing years (spring of the third year), and were followed by cash crops to benefit from the carry-over effect of N ($N_{carry-over}$) from the grass-clover leys. As a result, the share of permanent grassland was lowest in IFG and highest in FG. New leys in IFG were established as an understorey in winter wheat prior to the first production year, with a seeding rate of 29 kg ha^{-1} (70% *Lolium perenne*, 20% *Trifolium pratense*, 10% *Trifolium repens*). In the FG system, arable grass was renovated every 5 years, of which 4 ha were plowed in late summer followed by a catch crop for winter grazing for heifers. The remaining arable grass was renovated in spring and reseeded at a rate of 30 kg ha^{-1} (80% *Lolium perenne* and 20% *Trifolium repens*). Permanent grassland management and silage production was conducted according to the local recommended practice comprising 3–5 silage cuts on grassland (Loges et al., 2018a) and maize seeding at the beginning of May and harvest at silage maturity at the beginning of October (Komainda et al., 2018). Where swards were grazed, the residual biomass after each of 8–10 grazing cycles per year was clipped when necessary and the clippings left as a mulch.

On-Farm Research Design

Each of the four dairy farms (representing systems IC, SC, FG, and IFG) was observed for 2 years during the period 2011–2019. The farms were selected on the basis of the above-mentioned production data representing for SC and IC the average and best 25% with regards to management and milk yield in the state. The grazing systems represent systems that are not common for the time being, but proposed promising alternatives, in comparison with confined systems. The IC and FG systems were observed during the years 2010 and 2011, and farm SC from 2014 to 2015. The IFG was observed from 2017 to 2019; however, because of heavy droughts during 2018 the data for this year were discarded as they were not comparable to the other study years. Weather data were recorded at weather stations from Germany's National Meteorological Service (DWD) close to the experimental sites. Average rainfall and daily temperature during the vegetation period (April–Sept.) and experimental years were 434 mm (SD 82) and 14°C (SD 0.5). According to simulation runs for a 4 cut silage system with the grass growth model FOPROQ (Torssell and Kornher, 1983; Herrmann et al., 2005), used by national recommendation services to estimate the optimal cutting date for grass silage in the state, the average grass silage yields within the climatic region of the analyzed farms showed only small differences for the simulated yields [$\sim$11 t DM ha^{-1} (SD 0.7)], indicating comparable climatic conditions during the different vegetation periods and experimental years. Soils on the investigated farms were classified as sandy loams, with the texture ranging from 56 to 76% sand, 16 to 29% silt, and 7 to 16% clay. For IC and SC the most common breed in the research area Holstein-Friesian was used. In the FG and IFG systems farm managers chose cows with a lower weight to ensure early and late grazing could take place with a minimum of sward damage from trampling.

Farm Management Data

Common farm management and herd data were collected throughout the study period. These data contained herd information (e.g., replacement rate, weeks of lactation, milk yield), farm management data (e.g., area of land, land-use, soil tillage intervals, and grassland management) as well as purchased resources by the farm manager (e.g., supplementary feeds, fertilizer, agro-chemicals).

Forage Productivity

The aboveground biomass (AGB) on grassland was measured by hand clipping with shears prior to the silage cut or grazing event. The sampling area was 0.25 m^2 (with ten replicates per paddock) and the sward was cut leaving a stubble height of 50 mm. For all mown grassland there were 3–4 cuts, and for the pastures 3–11 rotations including silage cuts per experimental year according to the conducted grassland management of the different systems. The AGB for the pastures were further defined as AGB_{access}. In addition, enclosures were installed on the pastures to measure the biomass growth during grazing events ($AGB_{regrowth}$). After grazing the AGB residues ($AGB_{residues}$) were quantified by hand clipping as described above, but leaving 40 mm stubbles. The pasture-intake by grazing animals was calculated as:

$$\text{Pasture} - \text{intake} = AGB_{access} + AGB_{regrowth} - AGB_{residues} \quad (1)$$

For maize, ten plants in a maize row were harvested at silage maturity and cut at a stubble height of 20 cm. This procedure was replicated three times on each ha of maize. A subsample of $\sim$100 g for grass and 1,000 g for maize, respectively, was taken to determine plant dry-matter (DM) content after drying in an oven at 58°C until constant weight. In addition, subsamples of the grass-clover swards were separated into the fractions grass and clover. Prior to forage quality analysis, dried subsamples were ground in a two-step procedure: first passing a 5-mm (Retsch, GmbH, Haan, Germany) and subsequently a 1-mm screen (FOSS, GmbH, Rellingen, Germany). Forage N content and net-energy-lactation (NEL) were estimated by Near-Infrared-Reflection-Spectroscopy with a NIRsystems 5000 scanning monochromator (FOSS, Silver Spring, Maryland, USA). The total crude protein (CP) was calculated by multiplying a factor of x 6.25 to the respective N-content.

The average daily DM-intake of feed by cows was estimated according to the equation from Gruber et al. (2004), which takes into account the milk yield, the share of different forage types, the MJ NEL kg DM^{-1} and CP-content of feeds as variables. The average milk urea nitrogen (MUN) was calculated as a function of the average CP in forage (Spek et al., 2013) and DM-intake, whereas the daily N-excretion (N_{ex}) was estimated by daily DM-intake, its CP-content and live-weight following the approach by Nennich et al. (2005).

N_2O-Emissions and N-Leaching

Fluxes of N_2O on each field and dairy system were measured with the static closed chamber method. The minimum sampling frequency was once a week in all crops, taken between 10 a.m. and 12 p.m. In a pre-treatment, four collars for maize and grassland cut for silage and ten collars for pastures ($d = 60$ cm, $h = 15$ cm), made from polyvinyl chloride (PVC), were installed into the soil to a depth of 10 cm. The chambers were placed at uniform distances between the replicates in order to capture a representative area across each forage crop (avg. investigated field size 0.75 ha). The collars were removed during maize and grass-cut harvesting and tillage operations but remained in the grazed fields. During the flux measurements collars were closed gas tight with white PVC chambers ($d = 60$ cm, $h = 35$ cm). Gas samples were taken at 0, 20, 40, and 60 min after closure through a gas-tight septum on the top of the chamber using a 30 ml syringe. Samples were directly transferred into 12 ml pre-evacuated septum-capped vials (Labco, High Wycombe, UK). In the first 2 weeks after fertilizer application and grazing events, measurements were conducted more frequently at irregular intervals but at a minimum of two times per week. Gas samples were analyzed for N_2O and CH_4 through a gas chromatograph (SCION 456-GC, Bruker, Leiderdorp, Netherlands). The change of gas concentration in the chamber headspace during the measurement period was calculated by linear regression.

To determine N leaching to the groundwater over the winter period, soil water samples were taken using ceramic suction cups (Mullit, pore size 1 μm, length 54 mm, diameter 20 mm., ecoTech. Bonn, Germany). Sixteen ceramic suction cups were installed during the two experimental years and per crop at a depth of 75 cm and at an angle of 60° to minimize preferential flow and sampled from October to March. Prior to the first sampling date the suction cups were installed 6-months before the first sample was taken to ensure adequate time for soil settlement. To collect free drainage water a vacuum of 0.4 bars was applied to all suction cups. Soil water samples were obtained weekly until April. During sampling, four of the respective sixteen suction cup samples were mixed leading to four samples in total each week from every field. Leachate samples were stored at −20°C until analysis. Concentrations of total-N were determined photometrically using a dual channel continuous flow analyzer (SKALAR Analytical Instrument, Breda, the Netherlands). The amount of percolating water was calculated by a climatic water balance model, using weather and soil data gathered from the experimental site, actual evapotranspiration (Mohrlok, 2009), and specific crop coefficients (Löpmeier, 1994; Häckel, 1999) to correct evaporation.

Product Carbon Footprint (PCF)

The PCF for milk production of the four contrasting dairy farms was calculated using measured data for N_2O as direct emissions and N-leaching as an indirect source for N_2O-emissions from land-use. Additional indirect N_2O emissions from NH_3 volatilization in the cowshed were calculated according to Burgos et al. (2010). The emission factor (EF) for NH_3 volatilization from grazing animals were based on a review analysis of Sommer et al. (2019). Other gaseous N-emissions during manure application followed the methodology of the IPCC guidelines (IPCC, 2006; Mogensen et al., 2014). Methane emissions from ruminal digestion was calculated according to Schils et al. (2007).

In order to account for the on-farm soil carbon changes (SOC) of the tested production systems a simple approach developed by Petersen et al. (2013) was used. In this approach the different crops and management systems are compared to a reference system to estimate potential soil carbon changes. For the reference system a continuous long-term experiment with winter-rye cultivation, without any manure and fertilizer amendments, was chosen (for details see Merbach et al., 2000). Carbon inputs from roots and exudates were calculated as a ratio of AGB according to Taghizadeh-Toosi et al. (2014). For the various crops, different land-use factors (grassland:1, arable grass: 0.93, cropland: 0.8) and soil tillage factors (grassland:1.1, arable grass: 1.1, cropland: 1) were utilized, according to IPCC (2006). Emissions from external resources were adapted from the ecoinvent (vers. 3.3) data basis (econinvent, 2016). Estimates for the required off-farm cropland were based on the purchased supplements by the farm manager. Land requirement for soybean meal were calculated according to 10-year-average yield values (2007–2017) of soybean in Argentina (FAOSTAT, 2017), assuming an oil content of 20% and losses during the milling process of 2%. Supplementary feed is made from co-products from the production of plant-based oils, starch and sugar. Imported feeds with relevant by-products, such as oils and sugar were considered on the basis of the mass allocation for soy, canola, sunflowers and sugar beet (Dalgaard et al., 2008).

For the slurry exported from dairy farms for cash crop production on other land, it was assumed that every exported kg N would replace the equivalent of one kg mineral fertilizer. To follow the concept of consequential LCA production, costs for ammonium nitrate were used (ecoinvent 3.3) as the GHG savings for exported nitrogen in organic manures. Transport distances to cash crop producers and related GHG emissions were assumed to be negligible and ignored in this calculation. In the IFG, grass-clover was used as the forage base and the residual N in stubble and roots were considered as an export. The N from both above- and belowground crop residues was considered, with an equivalent of 0.51. This factor is based on observations from Huss-Danell et al. (2007) from a N-partitioning experiment on red-clover grassland. To calculate the global warming potential (GWP) per ha, the respective value for each trace gas over a life-span of 100 years was used ($CO_2 = 1$, $N_2O = 265$, $CH_4 = 28$) and expressed in CO_2-equivalents (CO_{2eq}). The efficiency of the systems with regards to climate change was calculated relatively, on the basis of the functional unit energy corrected milk (ECM), according to Sjaunja (1990).

Ammonia Emissions and Farm-N-Balance

Ammonia emissions per kg energy-corrected-milk (ECM) were calculated in accordance with the emission factors described above [section Product Carbon Footprint (PCF)]. The on-farm N-balance was calculated by the sum of nitrogen inputs and deduction of nitrogen outputs at farm-gate. For nitrogen inputs all purchased mineral fertilizers, straw, seeds and their respective N-contents, as well as biological nitrogen fixation (BNF) were considered. The BNF was calculated using the fraction of AGB derived from clover yield together with the modeling approach of Høgh-Jensen et al. (2004) and the N-cycling on pastures derived from N_{ex}. The N deposition from rainfall was used in the N-balance calculation, with a long-term annual average N deposition (1989–2005) in this area of 12.5 kg N ha^{-1} $year^{-1}$.

Nitrogen outputs consisted of milk and meat. The nitrogen export of milk was estimated by dividing the protein yield by 6.38 (ISO, 2014). For dairy cows the live-weight with a carcass weight of 46% was used. The protein content of carcass was assumed as 19% and converted to nitrogen using the factor 6.25. The annual meat export was calculated on the basis of the replacement rate. This also included the export of calves from the farm. After deduction of slurry demand on farm and gaseous-N losses during storage the surplus of slurry-N was taken as export-N. Fertilization management on the farm was considered to be in accordance with the farm management records.

RESULTS

Forage Productivity

Measured average forage yields on farm were comparable at 10–11 t DM ha^{-1} $year^{-1}$. The average CP contents differed, with 16, 15, 21, and 21% of DM in the IC, SC, FG, and IFG. However, when considering forage imports CP in the feed ratio increased to 20 and 16% CP for IC and SC, whereas CP slightly decreased in FG and IFG, due to the lower CP contents in the supplementary feed. Average net-energy lactation in forage was 7 MJ NEL kg DM^{-1} in all systems. NEL was mainly provided by silage maize in IC and SC and highly digestible grazed grass-clover in FG and IFG. Feed imports provided additional energy in total, in particular in SC, IC, and IFG, but without changing the average energy content of 7 MJ NEL kg $DM\text{-intake}^{-1}$. Calculated daily DM-intake showed a range of 17–24 kg day^{-1} for dairy cows. Lowest values were found in IFG and FG and highest in IC (**Table 2**).

TABLE 2 | Measured average DM-yields, energy- (MJ NEL kg DM^{-1}) and crude-protein (CP) contents from forage production and DM-intake (forage + supplements) from the two experimental years, and the predicted milk urea (MUN) contents and annual N-excretion (N_{ex}) per cow among the different systems (IC, intensive-confinement; SC, semi-confinement; FG, full-grazed; IFG, integrated-full-grazed).

Parameter	Unit	Farm type			
		IC	SC	FG	IFG
Forage production[a]	t DM ha^{-1}	11.3	11.5	10.5	11.1
	CP %	16.4	14.9	21.3	21.1
	MJ NEL kg DM^{-1}	7.0	6.8	6.6	7.0
Supplementary feeds[b]	t DM ha^{-1}	4.4	2.7	0.3	1.5
	CP %	31.7	19.8	16.6	13.1
	kg NEL kg DM^{-1}	7.7	7.8	8.1	8.4
Intake/cow[c]	kg DM day^{-1}	24.0	21.4	16.6	16.8
	CP %	19.8	16.4	20.7	20.5
	MJ NEL kg DM^{-1}	7.2	7.0	6.7	7.3
MUN[d]	mg N dL^{-1}	18.9	13.0	20.6	20.2
N_{ex}^{e}	kg N day^{-1}	0.53	0.42	0.40	0.38

[a]measured, [b]farm data, [c]Gruber et al., 2004, [d]Spek et al., 2013, [e]Nennich et al., 2005.

N_2O-Emissions and N-Leaching

Measured annual N_2O emissions were in the ranges of 0.7–4.7 in IC, 1.1–11.9 in SC, 0.9–2.6 in FG, and 0.1–0.7 kg N_2O-N ha^{-1} $year^{-1}$ in IFG (**Figure 2**). Highest mean annual N_2O emissions were measured in the SC system, which comprises N-inputs from mineral and organic fertilizers as well as N-excretion from grazed pastures. The N_2O-emissions from the grazed grass-clover swards that received no additional N fertilization were generally low, showing maximum annual emissions of 1.6 kg N_2O-N ha^{-1} $year^{-1}$ in FG. The IFG system showed similar emissions on permanent grassland, but had lower emissions on grazed arable grass-clover leys in comparison with FG. Higher emissions in the grazed arable grass systems in FG were mainly a result of the grazed catch crops during winter prior to grassland sowing in spring (data not shown). Annual N_2O emissions from silage maize were elevated in comparison with grassland in the IC and SC systems, with average emissions of 4.3 kg N_2O-N ha^{-1} $year^{-1}$. In comparison, grassland used for silage revealed 1.7 kg N_2O-N ha^{-1} $year^{-1}$. The total N-fertilization from mineral fertilizer and cattle slurry applied was on average 191 kg N ha^{-1} $year^{-1}$ for silage maize and 284 kg N ha^{-1} $year^{-1}$ for the permanent grassland utilized by mowing in IC and SC (**Figure 2**). Thus, emission factors for N-applied, calculated from the measured N_2O emissions, were higher for silage maize (2.3% of each kg N-applied) and slightly lower for mown grassland (0.6%) compared to the current EF of the IPCC guidelines. For grazing systems, the IPCC takes an EF of 2% of excreted-N into account. Annual N-deposits excreted by cows during grazing were calculated as 131 in FG and 141 kg N ha^{-1} $year^{-1}$ in the IFG. The calculated EF values were 1.2 and 0.6% in FG and IFG and thus higher for FG; however, they are in accordance with the IFG as currently

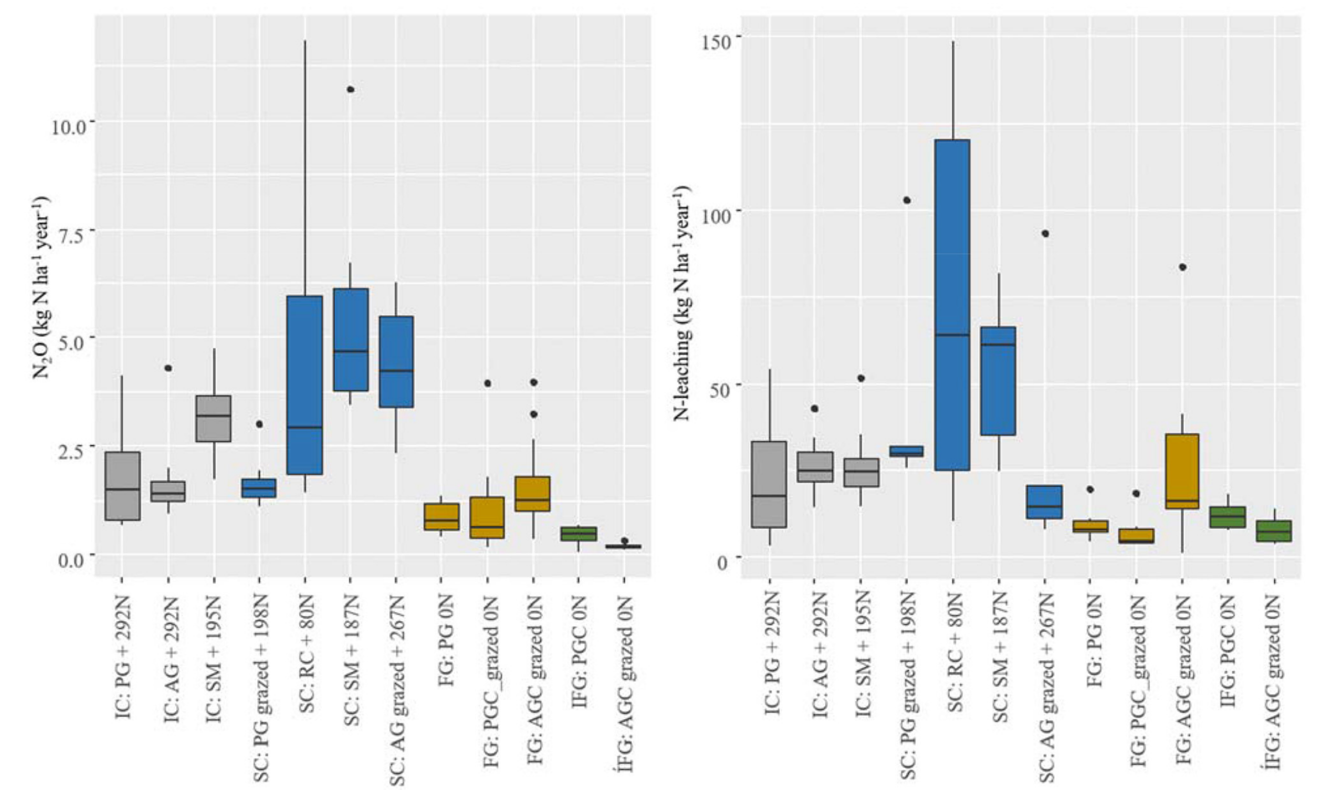


FIGURE 2 | Box-plots present the measured accumulated N_2O emissions and N-leaching to ground or drainage water losses across the different farm types (IC, intensive-confinement; SC, semi-confinement; FG, full-grazing; IFG, integrated full-grazing) and forage crops (PG, permanent grassland; AG, arable grass; RC, red-clover-grass; AGC, arable grass-clover; SM, silage maize; PGC, permanent grass-clover; AGC, arable grass-clover). The amount of N applied (kg N ha^{-1}) by mineral fertilizer and slurry is given in the figure legend. N-losses of two experimental years are shown. The box represents the 25th and 75th percentile. The black line in the box is the median. The whiskers represent the minimum and maximum values. Dots are outliers.

shown in the IPCC refinement report for other N-inputs in wet climates.

Nitrogen leaching was on average over the two experimental years 50, 25, 15, and 10 kg N ha^{-1} $year^{-1}$ for SC, IC, FG and IFG. High N-leaching losses were observed in particular for N-fertilized arable red-clover grass swards (73 kg N) and silage maize (37 kg N) in SC. For N-fertilized permanent grassland and arable grass in the SC and IC system, leaching losses of 31 kg N ha^{-1} were measured. Non-N-fertilized and mown permanent grass-clover revealed 16 kg N ha^{-1}; the grazed permanent grass-clover showed leaching losses of 24 kg N ha^{-1}, and grazed arable grass-clover swards revealed slightly lower losses of 21 kg N ha^{-1}. However, N losses in the latter were dependent on sward age with increasing increments of N-losses for each additional year of grazing management (data not shown).

Product Carbon Footprint (PCF)

The largest contribution to the total global warming potential (GWP) per ha in all systems was from enteric CH_4 emissions, as a result of ruminal digestion. In addition, with energy expenditure for milking and animal housing, the share was 45 and 44% in the IC and SC system (**Table 3**). Due to lower milk yields and lower share of other emission sources, the enteric fermentation had a larger contribution in the grazing systems, FG and IFG, and accounted, on average, for 66% in both systems. Taking the feed imports as well as the inputs of fertilizers and seeds into account, forage production showed the second largest share of emissions with 26, 28, 14, and 14% of GWP in the IC, SC, FG, and IFG systems. The third largest contributor in the IC and SC was manure management at the farm facilities. With increasing share of grazing (0% IC, 22% SC, 70% FG, and 80 IFG% expressed as a percentage of days on which they were grazed per year) the importance of manure management on the total GWP declined from 23 (IC) to 9% (IFG). Greenhouse gas emitted from the young stock showed a range of 6–14% of total GWP, with lowest shares in IC and IFG due to lowest replacement rates (see **Table 1**). Soil carbon sequestration reduced the GWP in all systems, as the high share of grass in the forage crop rotation, together with slurry inputs, led to positive soil carbon balances. Highest sequestration rates were observed in the IFG system due to the high acreage of 2-year grazed grass-clover leys (**Table 3**). Calculated annual sequestration potential was 0.24, 0.36, 0.47, and 0.56 t C ha^{-1} across the systems IC, SC, FG, and IFG. With the exception of SC all farms are eligible to receive credits for the substitution of mineral fertilizers by slurry exports. However, there were large differences among the systems with highest

TABLE 3 | Global warming potential (GWP) per ha in the different dairy systems and system units expressed in kg CO_2-equivalents (CO_2eq) per ha.

Parameter	Farm type			
	IC	SC	FG	IFG
			(kg CO_2eq ha^{-1})	
Dairy cow	**8,224**	**6,586**	**5,359**	**6,330**
CH_4^a/CO_2^b (%)	(87/13)	(88/12)	(93/7)	(95/5)
Young stock	**1,210**	**1,795**	**1,164**	**552**
Manure Storage	**4,225**	**2,491**	**889**	**777**
$CH_4/N_2O/NH_3$ (%)	(72/16/12)	(75/14/11)	(73/12/15)	(75/9/16)
Forage production	**1,814**	**2,257**	**914**	**245**
N_2O/N-leaching/NH_3/CO_2^c (%)	(55/4/9/32)	(73/7/6/14)	(66/5/5/23)	(40/11/26/23)
Inputs	**764**	**701**	**96**	**96**
Mineral Fertilizer, Lime/Agrochemicals/ Seeds (%)	(93/1/6)	(95/1/4)	(36/0/64)	(16/0/84)
Feed imports	**2,110**	**1,298**	**161**	**934**
Soil carbon storage	**−894**	**−1,327**	**−1,725**	**−2,063**
Credits	**−321**	**0**	**−211**	**−741**
N, P_2O_5, K_2O/BNF (%)	(100/0[d])		(100/0[d])	(16/84)
GWP	**18,346**	**15,128**	**8,583**	**8,934**
GWP + soil carbon	**17,452**	**13,800**	**6,858**	**6,870**
GWP + soil carbon + credits	**17,131**	**13,800**	**6,647**	**6,130**
			(kg ECM ha^{-1})	
Milk production	**15,817**	**11,512**	**7,420**	**10,394**
			(kg CO_2eq kg ECM^{-1})	
PCF	**1.2**	**1.3**	**1.2**	**0.9**
PCF + soil carbon	**1.1**	**1.2**	**0.9**	**0.7**
PCF + soil carbon + credits	**1.1**	**1.2**	**0.9**	**0.6**

[a]ruminal digestion, [b]milking and stable operation, [c]machinery operations, [d]not applicable.

TABLE 4 | N-balance of the prevailing farm types (IC, intensive-confinement; SC, semi-confinement; FG, full-grazing; IFG, integrated full-grazing).

Parameter	Farm type			
	IC	SC	FG	IFG
		kg N ha^{-1} $year^{-1}$		
N-inputs[a]	**349**	**265**	**155**	**180**
Purchased fertilizer	114	76	0	0
Feed imports	222	91	7	35
Straw	0	1	5	10
Seeds	0	0	1	1
BNF[b]	0	85	130	121
N-outputs	**120**	**65**	**62**	**131**
Milk	83	59	37	53
Meat	4	6	4	3
Manure	33	0	21	13
N-carry-over[c]	0	0	0	62
N-balance	**229**	**200**	**94**	**50**

Nitrogen inputs are represented by the purchase of fertilizer-N, feeds, straw, seeds and biological nitrogen fixation (BNF). N-outputs are generated by sold milk and meat as well as manure export. Exports of BNF (N-carry-over in root and plant residues) were only applicable in the integrated crop animal systems. A share of 0.51 of total BNF was considered as output to the arable system as plant residual matter (Huss-Danell et al., 2007).

[a]Aerial deposition included (12.5 kg N ha^{-1} $year^{-1}$), [b]Høgh-Jensen et al., 2004, [c]Huss-Danell et al., 2007.

exports in IC (**Table 3**). The accounting of credits for BNF as a by-product was only applicable in the IFG, as leys were part of ICLS. On the other farms N circulated only in the forage crop system leading to a potential excess of N (see section Farm-N-Surplus and Losses of Reactive Nitrogen). The PCF for each kg ECM produced was in the range of 0.9–1.3 kg CO_2eq with lowest values in IFG and highest in SC. Taking soil carbon sequestration and consequential impacts due to greenhouse gas (GHG) crediting into account, the PCF was reduced in all systems but was still lowest in IFG (**Table 3**).

Farm-N-Surplus and Losses of Reactive Nitrogen

The farm N-balance declined from 229 to 50 kg N ha^{-1} $year^{-1}$ in the order of IC, SC, FG and IFG. In the IC and SC systems, highest imports at farm gate were provided by mineral fertilizer and feed imports, whereas N-imports by supplements exceeded 200 kg N ha^{-1} $year^{-1}$ in the IC due to a high share of soybean meal. In the FG and IFG, biological nitrogen fixation (BNF) had, with 130 and 121 kg N ha^{-1} $year^{-1}$, the largest contribution to N-inputs, leading to comparable total average N-inputs per ha of 121 kg N ha^{-1} $year^{-1}$. Milk provided the largest N-export from the farm in IC (69%), SC (91%), and FG (60%) systems. However, these figures were different for the IFG, showing a share of 40%. Exports from BNF in the form of plant residual matter was only applicable in the IFG system, and this influenced the farm-N-balance positively (**Table 4**).

Total predicted and measured losses of reactive N from the farm were generally in accordance with the calculated farm-N-balance, showing slightly lower values (**Table 5**). NH_3 emissions from manure storage and N-application were the largest contributors with a share of 66–85% to the total N-losses. The total NH_3-emissions amounted to 160 kg N ha^{-1} $year^{-1}$ in IC, whereas in SC, FG, and IFG these losses were reduced by 37, 72, and 70%. The range of N-leaching on total losses was 13–31%, with highest losses in IC and SC. Measured N_2O-emission were with 2–3% of minor relevance in total. The N-footprint per kg milk produced was highest for SC and lowest for IFG (**Table 5**).

Considering the calculated N-balance (**Table 4**) and leaving the N-carry-over in IFG aside, 17, 23, 32, and 50% of N-losses

TABLE 5 | Measured and predicted losses expressed in kg N ha^{-1} of reactive nitrogen from the different systems (IC, intensive-confinement; SC, semi-confinement; FG, full-grazing; IFG, integrated full-grazing) as well as the N-footprint per kg energy corrected milk (g N kg ECM^{-1}).

Parameter		Farm type			
		IC	SC	FG	IFG
		kg N ha^{-1}			
Manure storage	**N_2O^a**	2	1	<1	<1
	NH_3^a	123	68	34	31
Forage production	**N_2O^b**	2	4	1	<1
	NH_3^a	37	33	11	16
	N-leaching[b]	25	48	16	9
Total N-losses		**189**	**153**	**63**	**56**
		g N kg ECM^{-1}			
Total N-losses ECM^{-1}		**12**	**13**	**9**	**5**

[a]*predicted,* [b]*measured.*

of the farm N balance were not accounted for in the IC, SC, FG, and IFG, respectively. However, when accounting for soil C sequestration, with the site-specific C/N ratio, N accumulation in the soil amounted to 24, 36, 47, and 57 kg N ha^{-1}. This reduced the percentage of N not accounted for to +7, +5, −17, and −1%.

The relative differences of environmental impacts compared to IC indicated a 18 and 43% lower PCF; 59 and 78% lower farm-N-balance, and 72 and 71% lower NH_3-emissions per ha in FG and IFG. SC showed a 11% higher PCF and 13 and 38% lower N-balance and NH_3 volatilization.

Milk yield per ha on the farm was 15,817, 11,512, 7,420, and 10,485 kg ECM ha^{-1}, resulting in a land requirement of 0.6, 0.9, 1.3, and 1.0 m^2 kg ECM^{-1} in IC, SC, FG, and IFG. However, taking imported land from purchased supplementary feeds into account, this relative perspective changed to 1.2, 1.2, 1.4, and 1.3 m^2 kg ECM^{-1}. With increasing milk yields per ha the farm N-surplus increased but did not show a clear linear trend among the systems. In contrast, the GHG emissions per ha correlated clearly positively with the N surplus on farm (**Figure 3A**). However, lowest N-surplus does not necessarily provide the lowest PCF (**Figure 3B**).

DISCUSSION

Forage Productivity

On sandy loamy soil, high productivity of forage crops can be achieved, particularly in areas with temperate maritime climate and evenly distributed rainfall (Loges et al., 2018a; Struck et al., 2019). The most important driver is the nutrient availability, which is mainly constrained by N (Biernat et al., 2020b). In high-input dairy systems, N is provided by slurry and purchased mineral fertilizers, whereas in low-cost systems the use of external N resources can be avoided by using forage legumes and their ability for BNF (Reinsch et al., 2020). The N available on farm, and consequently the total N in slurry, is further increased by imported N-rich feeds. Consequently, the forage DM yield in the different observed dairy systems did not differ significantly, as there was sufficient N available either through artificial N-fertilizer imports (IC and SC) or BNF (FG and IFG) on grassland. Nevens and Reheul (2003) reported from a 31-year ley-arable trial, on the same soil type as used in our study, that grazed leys provide similar amounts of forage to those of old permanent grassland swards, even at lower rates of fertilizer application. Low yield responses of pastures to N-fertilization were also reported elsewhere and can be explained by the N-return from grazing animals (Viljoen et al., 2020). This effect is more likely in grass-clover swards, where forages with high N contents are offered, leading to a higher N status in the soil during the grazing period. Moreover, the high yields from the observed leys, without any disadvantage to permanent grassland, can be explained by the chosen forage legume-based seed mixture, which can lead to benefits in herbage growth and subsequent yield (Nyfeler et al., 2011; Lüscher et al., 2014). Environmental factors are the largest explanatory variables that affect yield differences between years. Changes in the climate in northwest Europe are anticipated in the coming decades, and in response to these changes grassland productivity may increase by 11% by 2050 (Höglind et al., 2013). However, severe droughts will also become more likely, reducing the yield in those years considerably below the long-term average. In the IFG system, the leys were established as an understorey prior to the first production year. The rooting system of the established red-clover mixture allowed a higher yield resilience to droughts, in comparison with that of pure grass or grass-white clover swards (Lorenz et al., 2020). This is particularly important in this research area, where periods with lower rainfall often occur between May and June, increasing the inter-annual yield volatility.

In contrast to the very similar DM yield of the various systems, the observed forage systems differed in their ratio of CP and energy. The forage production in the IC and SC systems were dominated by grass and maize silage providing a ratio of 20–22 (g CP MJ NEL^{-1}), whereas FG and IFG showed an outstanding ratio of 31. However, with addition of the supplementary feeds, the ratio increased to 28 in IC but remained constant in SC as a result of a disadvantageous feeding strategy. Thus, the low-cost grazing systems (FG and IFG) produced a high share of CP on their farm itself, mainly as white and red-clover having a CP content, which is slightly lower but with a high potential for supplementary feed substitution at moderate milk yield losses (Schulz et al., 2018). However, improvements in feeding with balanced CP/NEL ratios across the grazing season become even more important in FG and IFG, as the forage quality is determined by the cultivation strategy of grass-clover leys and the typical annual growth patterns. Seeded grass-clover leys can show a high biomass accumulation by the forage legume components, which are determined by a higher proportion of grass in the total yield during spring, and a lower proportion of grass and more legume in late summer and autumn (Lorenz et al., 2020). Typically, this can lead to a surplus of ruminal-N and elevated milk urea contents in the second half of the year, therefore requiring use of energy-rich supplements necessary to maintain an optimal ruminal-N-balance and to reduce the risk of high urea nitrogen contents (Selbie et al., 2015), and also making NH_3- volatilization (Burgos et al., 2010) and N-leaching

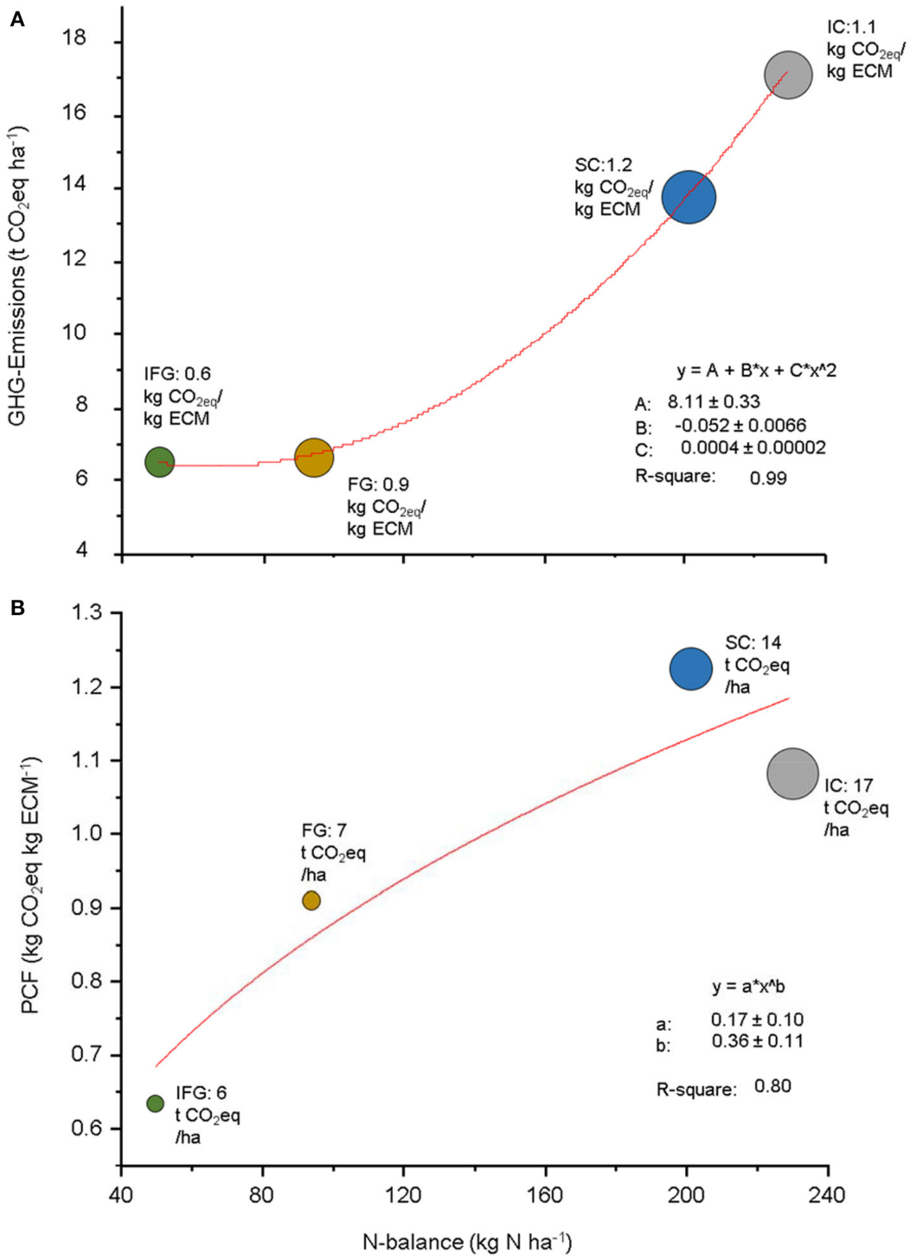


FIGURE 3 | Relationship between the farm-N-balance, GHG-emissions and product carbon footprint (PCF), among the different systems (IC, intensive-confinement; SC, semi-confinement; FG, full-grazing; IFG, integrated full-grazing). Results of the regression analysis are shown. Legends on the bubbles show either the PCF **(A)** or the GHG-emissions per ha **(B)**.

more likely (Cichota et al., 2012). In the IFG system, this was balanced by a moderate import of starch-rich components like cereals, which increases the milk yield per cow and ha compared to FG. In the FG system the swards were renovated every 5 years but were not part of an integrated crop system. Thus, the control of the desired sward composition was more challenging as renovated permanent white-clover grassland swards can show a high share of legumes 2–5 years after renovation, thereby producing a surplus of BNF and CP (Reinsch et al., 2020). This was present by highest CP-contents in offered forage and highest annual average milk urea nitrogen (MUN) in FG (**Table 2**) as result of a lack of supplementation of energy. Thus, with regard to the feeding strategy rotational grazed grass-clover swards can generate high yields, which can compete with intensively fertilized forage systems in terms of energy- and protein yields. However, the absence of moderate supplementation may cause undesired feed-backs on animal health and milk yields, and therefore a balanced CP to energy ration should be sought.

N_2O-Emissions and N-Leaching

The measured N_2O-emissions on the different farms showed typical patterns throughout the year, with high emission peaks during winter and after N-application (data not shown). Thus, in the N-fertilized arable and permanent grassland sites the calculated EF was close to the recommended value of the IPCC guidelines (IPCC, 2006), due to the dominance of annual emissions from peaks shortly after application. Higher emissions from silage maize in comparison with grass have already been reported elsewhere; this is due to high application rates of slurry during spring, which is incorporated into the soil prior to maize sowing (Struck et al., 2020). Under these conditions, with high amounts of N and easily decomposable organic matter, high N_2O-fluxes from soil heterotrophic denitrifies are likely. These can further be accelerated by additional N from soil organic matter mineralization induced by soil tillage activities (Struck et al., 2019, 2020). In the grazed systems, the annual emissions were significantly lower than the former IPPC default factor advised (IPCC, 2006); however, they are in accordance with the refined factors currently released for wet areas (IPCC, 2019). Such lower emission factors have also been reported from other grazing experiments in South Africa (Smit et al., 2020) and New Zealand (van der Weerden et al., 2020) as well as on the same experimental site over a long gradient of plant diversity and environments (Nyameasem et al., 2021). In addition to N-excreted by grazing animals, BNF was a major N-input in the IF and IFG systems. Even without the use of mineral N-fertilizers positive N-balances were achieved, particularly if the proportion of forage legumes within the ley is high (Reinsch et al., 2020). However, symbiotically fixed N is mostly captured in plant tissues, such as leaves and roots, but it becomes available erratically, depending on soil moisture, temperature, and soil and residue management. At the same time grasslands can show a large quantity of C and N sequestration in the soil, thereby avoiding the majority of N-losses (Loges et al., 2018a; Reinsch et al., 2018a). Moreover, the plant uptake of decomposed N is efficient in low-input systems characterized by low N_2O-emissions (Schmeer et al., 2014) and N-leaching (Reinsch et al., 2018b). Nevertheless, if BNF is not accounted for in N-fertilizer planning, N-leaching losses over the drainage period are likely to be increased, due to mineralization of the plant residues, in particular in temperate grassland areas where air temperatures often remain above 5°C during winter. This might explain the high measured N-leaching losses under red clover-grass swards in the SC system in both experimental years, where in addition to the predicted BNF of 305 kg N ha^{-1} there was also a N-fertilizer rate of 80 kg N ha^{-1}. However, in the grass-clover swards of FG and IFG only minor leaching losses were measured, which is in line with several other studies elsewhere on comparable soil types (Reinsch et al., 2018b; Biernat et al., 2020b). Under grazing situations N is frequently returned in the excreta. The higher availability of N in grazed swards changes the sward composition in comparison with mown red clover-grass toward one with a higher share of grasses with the consequence of a higher root length density, measured on the same site (Chen et al., 2016). This accelerates the N-uptake by the sward, which may have improved the N-efficiency of the grazed grass-clover system in FG and IFG in comparison with SC. Moreover, the SC system showed the highest N-footprint of all farm types leading to an acceleration of N in the system, which increased the level of total measured N-losses in all forage crops in comparison with IC, FG, and IFG. In this context, the farm management is of critical importance, as N-losses on the farm are exacerbated by disadvantageous feeding strategies, manure management and management of forage production.

Product Carbon Footprint (PCF)

Several studies have proposed that GHG emissions per product unit are negatively correlated with increasing milk yield per cow (Lesschen et al., 2011). Other studies mentioned that this has to be further differentiated by the production system used (Rotz et al., 2010; Zehetmeier et al., 2014; Lorenz et al., 2019). In confinement systems, large amounts of resources, usually imported, lead at some point to a compensation of reduced GHG-emissions per product unit on farm. In comparison, low-cost systems generate their milk yield exclusively from the on-farm produced forage, which in turn leads to lower milk yields per ha on-farm but also to a lower use of resources, thus contributing negatively to the PCF. Lorenz et al. (2019) found that a milk yield of 6,000 kg ECM per cow^{-1} and $year^{-1}$ provided by low-cost grazing is not disadvantageous in comparison to that of a confinement system, which uses a high share of imported supplementary feeds in order to achieve milk yields of 10,000 kg ECM per cow^{-1} and $year^{-1}$. This can be achieved by lower GHG emissions at the same level of feed-efficiency (kg of ECM produced per kg of DMI) (Drews et al., 2020). This was also demonstrated in our study, where IC and FG showed a similar PCF despite the large differences in milk yields per cow and the good herd performance in IC with a low replacement rate. Lorenz et al. (2019) further found that an increase in milk yield in grazing systems would show a higher GHG mitigation per kg ECM in comparison with additional milk yield increases in confinement systems, as the latter are already operating on a high production level. In our study the difference in PCF between FG and IFG accounted for 200 g CO_2eq per kg ECM milk, which is in line with the values reported by Lorenz et al. (2019), who predicted a GHG mitigation of 120 g CO_2eq due to an increase of animal performance by ∼1t ECM cow^{-1} $year^{-1}$ for low-cost grazing systems. With regards to the supplementary feed intake, the FGI showed a higher share compared to FG with 18 vs. 3%. Thus, it can be assumed that the FGI system, within its defined thresholds, is almost producing on its lowest level the potential PCF. In contrast, the mitigation potential by milk yield increases in IC was estimated to be 60 g CO_2eq kg ECM^{-1}, which provided already 35% of the daily DM-intake by supplementary feeds. The SC system showed the highest PCF in our study as a result of the poor feeding strategy and high N-losses. Using the production parameters on farm as an indicator, the SC system represents a business-as-usual scenario, with a milk yield and replacement rate comparable to a larger farm survey in this area (Drews et al., 2020). In comparison, the IC, FG and IFG represent more specialized systems of either intensive confinement or intensive grazing. These farms showed lower replacement rates and higher forage quality, indicating that specialized systems have higher management skills ensuring a higher resource efficiency and hence a lower PCF.

Further GHG mitigations were achieved on all farms when soil C-sequestration was also considered. Permanent grassland and leys offer the opportunity to sequester carbon, which on sandy loam soils has been reported to be as high as ∼4.8 t CO_2eq ha^{-1} $year^{-1}$ (Loges et al., 2018a). However, frequent soil tillage due to grassland renovation or land-use change to other forage crops can substantially reduce the potential C-sequestration to a lower level (Loges et al., 2018a; Reinsch et al., 2018a). Thus, after 2 years of ley farming most of the sequestered carbon can be lost during the following arable phase, if non-appropriate soil tillage practices are used. This somehow increases the uncertainty in evaluation ICLS (Reinsch et al., 2021) and potentially overestimates the sequestration rate in IFG as a high share of leys were present. However, the same uncertainty is given for permanent grassland in IC and SC as old swards with a high external N-input are likely to represent a C source rather than a considerable sink (Poyda et al., 2021). Additional C-sequestration was achieved by the return of animal excreta, regardless of whether slurry was applied or the deposition of dung from grazing animals were considered, the recycling of C and nutrients increases biomass yields and thus higher allocation of C plant residues. Loges et al. (2018a) found that young permanent grass-clover swards, when managed under cutting and fertilized with a moderate application rate of cattle slurry, will increase the C-sequestration by about 500 kg C ha^{-1} in comparison with management without slurry-N (Loges et al., 2018a). This rate is in line with a maximum predicted sequestration rate of 560 kg C ha^{-1} in IFG. Even though for permanent systems the duration of highly positive sequestration rates is limited, even after 20 years no equilibrium is reached on sandy loamy soils (Reinsch et al., 2018, Reinsch et al., 2021). The soil C-sequestration on external farms due to the exported slurry was ignored in this study, thereby likely underestimating the GHG savings from manure exports, which was only accounted for by crediting the substitution of mineral fertilizer using the nutrient contents in the slurry as a reference. Further crediting was applied for the IFG as plant mineralizable-N can be transferred to the integrated cropping system by using the same piece of land. The efficiency of plant removals is dependent on the soil tillage management and the post-cropping systems, whereas removal of leys in spring guarantees a higher N-use efficiency (Biernat et al., 2020b). However, plowing of grass-clover leys can cause distinct N_2O-peaks as N can become enriched in the upper soil layer at warmer temperatures that coincide with low rainfall during spring (Reinsch et al., 2018b). Consequently, such credits have to be taken with care, as the potential substitution of mineral fertilizers, which we accounted for in the subsequent cropping system, relies on minimal N-losses. Costa et al. (2020) reviewed 3,180 articles on the effect of integrating legumes within crop rotations and found considerable knowledge gaps in taking the legume-N carry-over effect into account in life-cycle-assessment (LCA) studies. They recommend that full crop rotations should be evaluated rather than to focus on only one crop. This applies also to ICLS and further research is needed to apply evidence-based results of cash crop producers (Biernat et al., 2020a,b) to our evaluated dairy systems. However, we argue that this credit gives the maximum threshold of a best-practice approach achieving a PCF+soil carbon+credits of 0.6 kg CO_2eq kg ECM^{-1}, indicating a mitigation potential of 600 g CO_2eq kg ECM^{-1} along the gradient of SC>IC>FG>IFG on sandy loamy soils. It has to be noted that the PCF calculation did not include emissions from produced infrastructure (e.g., machinery, cowshed). In grazing systems there is lower requirement for capital goods, of which the FG and IFG systems would further benefit in terms of their resource use. However, these investments need only to be considered for a specific duration of PCF calculation and therefore it depends on the age of the investments and their lifespan. Therefore, estimates on capital goods are difficult and are not influenced by the management strategy in the short term, and for these reasons are often not considered in LCA studies (Yan et al., 2011).

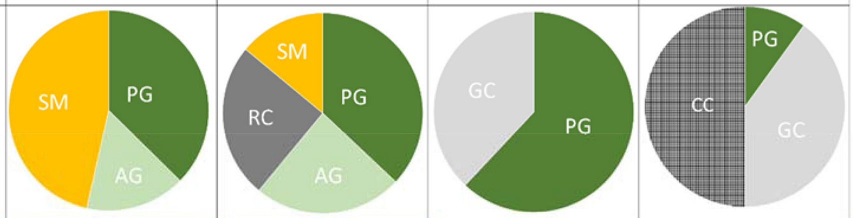
Farm-N-Balance and Losses of Reactive Nitrogen

The region where the study was conducted currently accounts for around 1 Mio. ha of agricultural land, which is dominated by specialized intensive arable cropping and dairy systems. Taube et al. (2015) estimated that in districts in this region, where dairy units are typically located, the average farm-N-balance exceeds 150 kg N ha^{-1}. Several programmes were released to counteract such high N-surpluses. The main foci during the last years have included fertilizer planning recommendations, legal adjustments in the fertilizer regulation, and efforts to strengthen the N-exports from animal husbandries to the regions with intensive cash-crop production. However, latest reports show that these attempts are not successful in reducing the N-surplus in the dairy sector significantly (Henning and Taube, 2020). The main reason for this is that animal manures are prone to high N-losses by NH_3-volatilization. Thus, the majority of N-losses in the IC and SC systems occurred due to the manure management. Mitigation can be achieved on the farm by manure storage covers and low emission spreading techniques (Maris et al., 2021) or slurry acidification (Seidel et al., 2017). However, mitigation of NH_3- would increase the N-content in applied slurry, which in turn decreases the possible application amount of manure on the farm itself and thus requires export, which is often limited by large transport distances. Another option is to reduce the amount of mineral fertilizer-N. This can be sought by the mentioned efficient use of animal manures (which in the EU is restricted to 170 kg N ha^{-1}) and the use of legumes. Even though BNF is an efficient way to capture N in crops, it represents an N-input in the system, which has to be considered in the fertilizer planning. Otherwise, the farm-N-balance cannot be improved significantly. The Baltic Marine Environment Protection Commission (HELCOM) further suggests that the share of grazing should be increased to reduce NH_3 pollutants to marine bodies. Due to these explained causalities, the farm-N-balance and total N-losses decreased with the share of grazing and reduced fertilizer inputs. Accordingly, the nitrogen-use efficiency (NUE) for IC, SC, FG and IFG is 34, 24, 40, and 72%. These figures are in the range found by other authors (Löw et al., 2020), although Löw et al. (2020) also found slightly increasing NUE for confined systems in comparison with grazing. Their finding mainly relies on their particular circumstances, as low-cost grazing systems using forage legumes as the N source were not taken into account, making mineral N-imports of ∼178 kg N ha^{-1} necessary. In contrast, in our investigated system FG and IFG showed self-sufficiency of N as a result of BNF. Despite the absence of mineral fertilizer use and high share of grazing the FG systems still revealed a farm N-balance of 94 kg N ha^{-1}. However, due to the high share of pastures a high share of the farm surplus is related to N stock changes in organic matter, rather than to losses of reactive N to the environment, which were quantified as <65 kg N ha^{-1} $year^{-1}$ in FG. With regards to the calculated NH_3- losses on pastures the current IPCC factor of 0.2 for N-excretion and slurry was applied. The majority of NH_4-N, which after its deposition is prone to NH_3-voltalization to the air, is present in the excreted urine. The DM content of urine (∼1% DM) is low in comparison to slurry (∼8% DM) ensuring a fast infiltration into the soil, where further NH_3-losses are avoided. However, using the milk urea content as a proxy, highest values were found for the FG system, making a potential overestimate of NH_3 questionable. Further reductions could be achieved by an optimized feeding strategy (see section Forage Productivity) or urease inhibitors. Nevertheless, limits in further reduction are reached as N-residuals enriched by BNF accumulate, if high shares of legumes are sought. Further mitigation can be achieved in the ICLS, where the carry-over effect of legume-N can be used by subsequent crops as illustrated in the IFG.

Pros and Cons of the Examined Systems

In our comparison of four potential dairy production systems based on farm management data, measurement results and empirical methods, the IFG systems as examples for and ICLS (level iii) approach performed best with regards to the environmental impacts per ha and per product unit but also on a very high-level regarding land use efficiency. At the same time adequate milk yields and forage yields were generated, which were comparable to SC systems. This was mainly provided by the low resource use of external inputs and high forage yields from grazed grass-clover leys. The additional credit of N-carry-over to a potential cash-crop system increased these benefits further and might have positive effects on the cash-crop system as well, if the N status in the soil as a result of the advantageous pre-crop (2 years of leys) are taken into account in the fertilizer planning of the cash crop producers. In comparison, farms that are focused exclusively on dairy, such as IC, SC, and FG, are not capable of reducing their N-surplus below 90 kg N ha^{-1} because of the continued N-accumulation in the soil and volatile N-losses. Comparing the environmental impacts from specialist pure confinement or full-grazing, the IC system showed on the one hand a higher N-surplus and N-footprint per ECM milk compared to the low-cost FG, but only slight differences in the PCF. This implies a higher negative impact on a regional scale (e.g., on groundwater and surface water quality) in the IC but the differences considered on a global scale (i.e., potential influences on climate change) are negligible. However, several uncertainties have to be considered as the environmental impacts from external resources, e.g., imported supplementary feeds, can show wide differences depending on its origin (e.g., deforestation issues), which cannot be controlled at the regional level or by the producers themselves, indicating a higher uncertainty of results for IC and SC compared to FG. Nevertheless, according to the results obtained here and in the context of sandy loam soils, further improvements at regional and global levels can only achieved if N and C-cycles are coupled better by integrating dairy farming into an ICLS (Soussana and Lemaire, 2014).

Highlighting the disadvantages of an ICLS in combination with low-cost grazing, it has to be considered that the milk yield per ha was considerably lower compared with that of the IC. This can lead to income losses, though this will depend on the milk price and feed costs. At present, specialist IC systems in combination with large herd sizes (economy of scale) may have a higher potential to compete financially with the world milk market. In comparison, average dairy farms such as SC currently having a negative turn-over (after deducing of feed costs) (LKSH, 2019). However, low cost-grazing systems provide forage at low costs resulting in high revenue per kg milk solid (White et al., 2002). Continued technical innovation increasing animal performance from grazed grass, increasing herd genetic potential and developing labor efficient lower fixed-cost systems are essential in this context (Dillon et al., 2008). Moreover, dairy production in the EU also relies on subsidies. With regards to the current CAP, environmental indicators (e.g., GHG emissions, farm N-surplus, agro-biodiversity, and animal welfare) are becoming of increasing importance in order to achieve the additional public payments (EU, 2021). This may, in turn, increase the farm revenue considerably, if environmental services linked to dairy production are fulfilled. Beyond these policy developments, there is also a continuous increase in consumer acceptance of sustainably produced dairy products, and increased readiness by consumers to pay a higher price for labeled produce that reflects this (Kühl et al., 2017). However, it also has to be highlighted that specialized confinement systems are less dependent on soil physical and soil chemical properties, as the utilization of grass and maize by cutting is generally easier than managing intensive rotational grazing. In addition, high grazing yields can be only maintained if soils and swards are not easily damaged by overgrazing or trampling, even when high stocking rates are necessary to fulfill the economic requirements for productivity per ha. Moreover, water availability during summer plays a crucial role as yield losses due to drought would make undesired feed purchases necessary, and thereby reduce the efficiency of the proposed grazing systems. Irrigation as an alternative solution would require investment and processing cost as well as questionable resource efficiency in areas where access to groundwater supplies is limited (Emadodin and Reinsch, 2018). Moreover, irrigation in grazing systems can increase undesired GHG emissions from pasture land considerably (Smit et al., 2020). Therefore, specialized IC systems will continue to play an important role in the future on the export markets, and structural change is expected to continue to disadvantage the SC system. There are additional constraints, if ICLS systems for dairy are sought at

	IC: Intensive-Confinement	SC: Semi-Confinement	FG: Full-Grazing	IFG: Integrated Full-Grazing
Land-use				
Fertilizer-Agrochemical demand	High	Medium	Low	Low
GHG emissions	High	Medium	Low	Low
CO_{2eq} /kg ECM	Medium	High	Medium	Low
Farm-N-balance	High	High	Medium	Low
N/kg ECM	High	High	Medium	Low
Productivity	High	Medium	Low	Medium

SM: silage maize; PG: permanent grassland; AG: arable grass; RC: red-clover grass (arable); GC: Grass-clover (arable); CC: cash-crop

FIGURE 4 | Overview of different ecosystem services and productivity provided by the different land-use types and resource efforts in the investigated prevailing dairy systems.

high use intensities. The claimed high milk yields at balanced CP/NEL ratios can make supplementary feeding necessary. On the one hand they could be produced locally; for instance, in the IFG system cereals for energy supplementation were provided in the cash-crop unit. On the other hand, however, increasing land consumption would accelerate local competition for food vs. feed. In comparison, most confinement systems in northwest Europe import a high share canola meal, which is a by-product of the oil industry (Broderick et al., 2015). van Hal et al. (2019) mentioned that the use of by-products, which are unsuitable for direct human consumption, increases the overall efficiency of a system even in the LCA perspective. Thus, the evaluated IFG system in our study needs further improvements as more then 80% of the supplementary feeds were provided from locally grown cereals. More maize grown for silage instead of cereals as an additional crop rotation segment might be an appropriate option regarding land use efficiency; however, on the basis of this study integrated dairy systems in the cash-crop sector may provide several positive opportunities (**Figure 4**) and should be implemented into the local policy.

CONCLUSION

Considering the environmental goals of the EU (e.g., "Green Deal") for the agricultural sector, there is a need to identify best strategies for agricultural land use linked to dairy systems. An important question concerns the current dominant high input/high out models, and whether they are appropriate for the land-use challenges of minimizing carbon and nitrogen footprints and for maintaining appropriate levels of biodiversity. The on-farm research study on four farms representing different strategies for land use and milk production on sandy loam soils in northwest Germany has confirmed that ongoing intensification in the dairy sector is not in line with the need for reductions in GHG and nitrogen emissions per kg ECM produced on the regional level and thus not in line with ecological intensification. Full-grazing systems in areas with adequate rainfall and appropriate soil conditions offer the opportunity to improve the overall efficiency but only when low input systems are sought. However, the farm-N-balance as well as impacts on climate change can be improved further if integrated systems are favored. This requires exchanging by-products and soil fertility in the context of a local spatial distribution and by making all arable systems more resilient. This study provides a first step toward further analysis and extrapolation regarding the economic resilience of the proposed system in the future.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

FT, RL, and TR: conceptualization. TR and CL: writing original draft preparation. CK and TR: data analysis. IV, FT, CSM, and RL: writing—review and editing. CK: visualization. FT: supervision. FT and RL: funding acquisition. All authors contributed to the article and approved the submitted version.

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Building the GLENCOE Platform -Grasslands LENding eConomic and ecOsystems sErvices

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To feed the rising population whilst also preserving ecosystem functions, creative solutions are needed for the ecological intensification of natural grassland-based livestock systems. In Uruguay, natural grasslands are the main nutritional resource for livestock production. In these ecosystems, cattle and sheep graze together all the year round, and grasslands are frequently heavily grazed. Considerable research has been generated concerning grassland management, but there is still no knowledge about the impact of decision rules that supports management actions on long-term ecosystem functioning, at the system level. To meet this deficit, a participatory working group of farmers, researchers, and consultants have developed the GLENCOE platform. This platform is a large-scale facility, supported by INIA-Uruguay, designed to answer the following question: How to intensify the grazing management to improve the sustainability of livestock systems based on natural grasslands? To build the platform three steps were followed: (I) definition of the research problem using a problem tree analysis; (ii) conceptualization of the platform and the design of the grazing systems to be evaluated; and, (iii) spatial allocation of the grazing systems according to the variability of soil, slopes, and seasonal dynamic of vegetation indexes. These criteria were considered across farmlets that were equivalent in the initial stage, allowing causal inferences for the systems trajectories on productive and environmental traits. The platform is composed of three independent farmlets of 50 ha each, where multiparous Hereford cows and Merinos wethers co-graze under three grazing management systems. Each farmlet is managed according to different spatio-temporal decisions of the specific management of vegetation communities, grazing methods, and the stockpile of forage that is allowed by the number of the existing paddocks. Farmlet-1; comprises less decisions (2 paddocks), Farmlet-2; intermediate (8 paddocks), and Farmlet-3; high level of decisions (32 paddocks). This innovative platform will be used as a participatory and interdisciplinary space for research and co-learning of management on processes that can only be observed in long-term evaluations, and at farmlet scale. We expect that this new approach will contribute to the developement and implemention of sustainable grazing management systems in Uruguay.

Keywords: sustainable intensification, beef-cattle, rangelands, campos grasslands, mixed-grazing, wool

INTRODUCTION

A major challenge for the primary production sector is increasing the production and quality of agricultural products and maintaining the supply of ecosystem services in a scenario of high climatic and price variability. In Uruguay, extensive beef cattle and sheep production, based on native and high-diverse grasslands, has contributed to the Uruguayan economy through the centuries. In these systems, animals graze all through the year, and pastures are often heavily grazed, due to a mismatch between forage demand and supply. In a context of climate and land use changes, developing grazing management and system planning strategies to increase livestock production on native grasslands whilst simultaneously maintaining or improving ecosystem services provision is the new challenge.

Uruguayan research institutions have generated important knowledge on grazing management at the plot and paddock scale, but there is a need for long-term studies on native grasslands to answer questions at the farm (system) level (Jaurena et al., 2021). As discussed by Briske et al. (2008), traditional research with rigid protocols does not consider the systemic perspective which is involved in farm systems. In Uruguayan livestock farm systems, the asynchrony between forage on offer and demand frequently leads to heavy grazing pressure and consequently to low animal productivity and negative environmental impacts, such as reducing plant diversity (Fedrigo et al., 2018) and increasing greenhouse gas emissions (i.e., N_2O, Chirinda et al., 2019; CH_4, Cezimbra et al., 2021). Therefore, the long-term consequences of alternative grazing management design on production and environmental variables needs to be evaluated in the long-term.

In this short paper, we present a conceptual framework and early methodological steps to build a long-term experimental platform (farmlets) to evaluate the impact of alternative grazing management systems on primary and secondary production and on the supply of ecosystem services.

MATERIALS AND METHODS

To build the platform, three steps were considered: (i) The definition of the research problem, (ii) The conceptualization of the platform and design, and (iii) The spatial allocation of farmlets. A baseline data set will be collected to obtain a reference point for the evaluation of the system trajectories across four dimensions (economic, environmental, human, and emergent proprieties). We will evaluate regulation and support ecosystem services (according to the Millennium Ecosystem Assessment, 2005 classification) using two approaches: one based on measurements of different dimensions of ecological integrity (Blumetto et al., 2019) and the other through the use of synoptic indicators of ES "bundles," based on remote sensing (Paruelo et al., 2016) at the plot level.

A data repository will be also available as part of the participatory process.

Definition of the Research Problem

In a workshop (13th-18th August 2018), a multidisciplinary group of 20 experts defined the research problem using a "Problem Tree Analysis" (Cazzuli et al., 2020). Low plant and animal production rates and its high variability were the core problem of livestock systems based on native grasslands. Low digestible forage harvested by ruminants and low forage to animal product conversion efficiency were identified as causes (roots) of actual farm systems, and led to two main effects ("branches"): (i) reduced ecosystem services supplying and (ii) reduced stability and resilience of the system, which embodies economic, environmental, and social traits.

Throughout this platform we will investigate the consequence of paddock size and grazing management of native grassland communities on the structure and functioning of the vegetation, animal production, soil quality variables, economic outputs, and ecosystems services.

Conception of the Platform and Design of the Grazing Systems to Be Evaluated

We used a co-innovation approach (Albicette et al., 2017) with the participation of researchers, extension agents, and farmers in selecting the platform treatments and management protocols as well as in future evaluation and monitoring. During 2019, three half-day workshops were conducted with the working group to discuss proposals and define strategies for the platform design.

The platform will be placed at INIA-Glencoe Experimental Station (Paysandú, Uruguay) and will cover an area of 150 ha of native grasslands on basaltic shallow soils. The platform will comprise three independent farmlets of 50 ha each, where multiparous Hereford cows and fine wool Merinos wethers will be co-grazing under three grazing management systems. Farmlet-1 comprises less spatial and temporal decisions (two paddocks) and is considered the reference system, Farmlet-2 is intermediate (eight paddocks), and Farmlet-3 has more spatial and temporal decisions (32 paddocks).

For all three farmlets, practices such as breeding season and stocking rate adjustment are assumed to be adopted. Each farmlet will be managed at the greatest intensity of spatial-temporal decisions that the number of paddocks allows, e.g., more possibilities to stockpile forage in Farmlet-3. At the starting

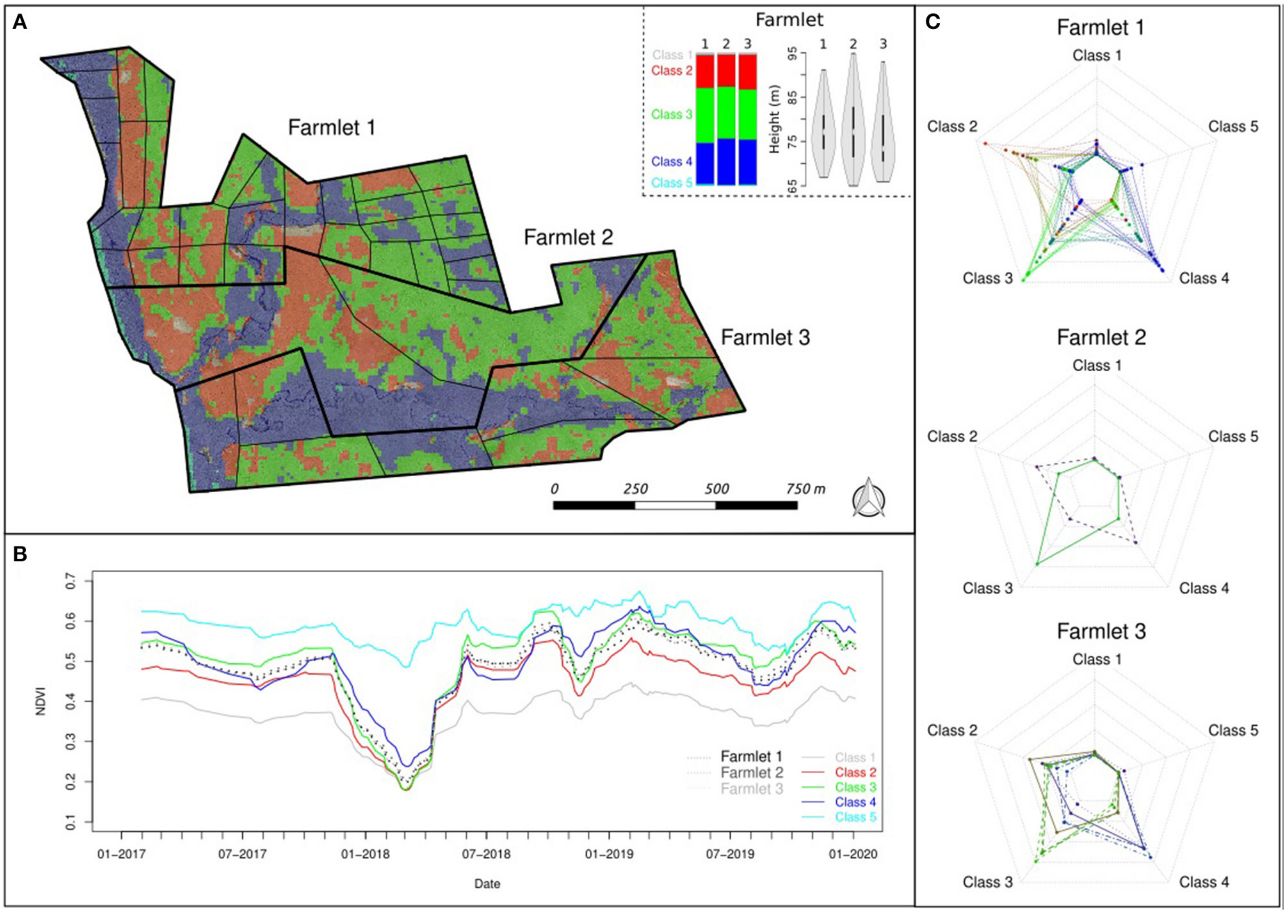

FIGURE 1 | **(A)** Map of vegetation classes (1, low vegetation cover, rocks; 2, shallow soil uplands; 3, deeper soil uplands; 4, depressed areas and lowlands; 5, streams), spatial allocation of farmlets (thick lines) and paddocks inside farmlets (thin lines). Box showing the proportions of vegetation classes and height distribution bay farmlet. **(B)** NDVI time series showing differences between the five vegetation classes (colors) and similarities between the three farmlets (grays). **(C)** Spyder plots showing the proportion of vegetation classes for the different paddocks of each farmlet. Colors of the points and lines representing each paddock are in line with the proportion of the more frequent vegetation classes (2 = red, 3 = green, 4 = blue). The greater the number of plots in the farmlet, the greater the chances of obtaining plots dominated by a vegetation class.

point of the study, all farmlets will have the same animal stocking rate (0.6 AU), defined as the safe stocking rate for basaltic shallow grasslands (Berretta, 1997) and a cow:wether (1:1) ratio. Stocking rates of each farmlet will be adjusted every year using a decision rule that considers the forage availability and body condition of the animals. Short-term decisions of all the farmlets' grazing will be based on pasture height targets, to achieve optimal grazing intensities in some paddocks while others could be stockpiled for future use during forage shortages. A minimum of 10 years of evaluation is planned for this study.

On Farmlet-1, we aim to achieve an acceptable profit from animal production with low investments on fencing and little working-time allocated to monitoring pasture and making decisions (once a month). On Farmlet-2, we intend to improve the profit from animal production though a medium level of investments in fencing and time spent on monitoring pasture and making decisions. Management decisions about animal movements on paddocks and stockpiling of forage will be taken once a month in autumn-winter and every 15 days at spring-summer when pasture growth is highest.

On Farmlet-3, we aim to improve profit from animal production with a higher level of investments in fencing and time spent on monitoring pastures and on making decisions. Monitoring will be made weekly at the autumn-winter season, and twice a week at the spring-summer season.

Spatial Allocation of Farmlets

The farmlet reflects the spatial variability of typical farms, so we defined a minimum area of 50 ha for each farmlet at the cost of losing the replicating units of the experimental design. This choice led to an important assumption: the farmlets must be under equivalent starting conditions in order to allow the evaluation of the different grazing systems.

To divide the total area into three farmlets with their corresponding paddocks we considered the variability in the seasonal dynamic of vegetation indexes and topography. We used the Google Earth Engine platform to obtain a total of 161 images from SENTINEL 2 (Level 1C;10 m spatial resolution and <20% of cloud cover) from January 2017 to December 2019, and the 30 m spatial resolution from Digital Elevation Model DEM (SRTM). NDVI time series showed contrasting growing seasons (from October to March): a drought (2018–2019) and a wet year (2018–2019). Second, we used GRASS software v.7.2 (2017) to calculate descriptors of vegetation functioning based on the NDVI, slope, and median NDVI for the dry season and date of maximum NDVI and median NDVI for the wet season. The temporal resolution of the data used was 10 days. Then we performed an unsupervised maximum likelihood classification based on the four descriptors. We obtained five vegetation classes based on NDVI. Third, we used QGIS software to divide the area into the three farmlets with their corresponding paddocks based on the classification, the DEM, and 8 cm resolution drone image from December 2019 (**Figure 1A**). We tried to create farmlets as similar as possible to the proportion of vegetation classes (**Figures 1A,B**) and altitude distribution. After that, grazing management systems were randomly allocated to each farmlet. Finally, farmlets were subdivided into the corresponding number of paddocks considering uniform vegetation classes (**Figure 1C**).

CONCLUSIONS

This platform is an innovative project in Uruguay and will allow us to identify emerging proprieties of the systems to create resilience and ecosystem services. Moreover, this platform would be useful for monitoring key indicators to assess ecosystem services and, therefore, to advise public and private decision-makers. We expect that this new approach will contribute to developing more profitable and sustainable grazing management systems for Uruguayan livestock production, which will be also useful for livestock production systems in similar ecosystems.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation, to any qualified researcher.

ETHICS STATEMENT

The animal study was reviewed and approved by Comité de Uso de Animales de Experimentación del INIA.

AUTHOR CONTRIBUTIONS

TD, MJ, JS, GC, EN, VC, FL, and JP have contributed on discussions and on platform conception. MD have contributed on acquisition and treatment of satellite images for field desing. All authors contributed to the article and approved the submitted version.

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Pasture-Based Dairy Systems in Temperate Lowlands: Challenges and Opportunities for the Future

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Improved efficiency in dairy systems is a significant challenge for the future, to meet increased food demand while competing for inputs, adapting to climate change, and delivering ecosystem services. Future grazing systems can play a major role to supply healthier foods within systems with a reduced reliance on fossil fuels and chemical inputs, while also delivering environmental, biodiversity, and animal welfare benefits. Can we design lower-input systems that deliver efficient levels of output in a positive environmental context? Lower-input systems will have a lower reliance on concentrates and inorganic fertilizers, and an increased reliance on extended grazing seasons and high quality forage. Multiple strategies will be needed to maximize nitrogen use efficiency, including a strong reliance on legume-based swards that displace inorganic nitrogen fertilizer. Expected environmental benefits include a reduction in GHG emissions and nitrate leaching, an increase in C sequestration and a reduced reliance on the use of herbicides and pesticides. In comparison with confinement feeding systems, the relatively low energy density and high climate sensitivity of grazing diets requires both effective pasture management and robust and adaptive animals. The appropriate cow for grazing systems must be able to harvest pasture efficiently by re-calving every 365 days to efficiently utilize peak pasture supply, achieve large intakes of forage relative to their genetic potential for milk production (i.e., aggressive grazers) and be adaptable to fluctuations in feed supply. Legume-based multi-species grassland mixtures can maximize the use of symbiotically-fixed nitrogen, and displace the use of inorganic N fertilizer. There is a need for system-scale experiments that use legume-based mixtures within paddocks, and in grassland leys within crop rotations. Moreover, lower-input systems will need a combined focus on research and knowledge transfer for rapid testing and implementation. New opportunities and requirements will arise as policy, society, and the markets demand a higher level of environmental sustainability from food systems and products. This raises the possibility of public-private partnerships for the demand and reward of provision of environmental benefits. To deliver these benefits, future food systems will need to be redesigned to incorporate the enhanced supply of a range of ecosystem goods and services, which should be better incentivized through the market price returned to producers.

Keywords: dairy cows, pasture, sustainable grazing, biodiversity, policy, ecosystem services

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INTRODUCTION–CHANGING DEMANDS ON FOOD SYSTEMS AND CLIMATE SMART FARMING

Across the world, agriculture plays a crucial role not only in supplying food, but in shaping rural areas, preserving landscapes and cultural practices and heritage. The coming decades are likely to see increased pressures on agricultural systems, to continue to provide for an expanding and increasingly wealthy global population, and on the supply side, from greater competition for inputs and climate change (Godfray and Garnett, 2014; Zijdeman and Ribeira da Silva, 2014). The world's population is expected to grow from 7.6 to 10 billion between 2017 and 2067 (FAO, 2017) while the global demand for milk is expected to increase by 48% between 2005 and 2050 (Alexandratos and Bruinsma, 2012). As global incomes increase, diets typically shift from those comprised of mostly grains, to diets that contain a greater proportion of meat, dairy, and eggs (Tilman et al., 2011; Kastner et al., 2012). It is estimated ∼40% of the world's population will undergo this dietary shift by the year 2050 (Delgado et al., 2009). Society has grown accustomed to low food prices and at the same time, expects agriculture's environmental footprint to be reduced, to protect biodiversity and to provide products of unprecedented nutritional value. The longstanding challenge of achieving global food security through sustainable agriculture is particularly acute as world agriculture is a leading pressure on the environment. Today, global agriculture, forestry and other land use activities account for 13% of carbon dioxide (CO2), 44% of methane (CH4), and 81% of nitrous oxide (N2O) emissions from human activities globally, representing 23% of total net anthropogenic emissions of GHGs (IPCC, 2019). At the same time, loss of biodiversity and pressures on ecosystem services are among the most pressing global environmental challenges while land cover and land use change are leading contributors to habitat fragmentation, habitat loss and reduced biodiversity (Newbold et al., 2015; Ceballos et al., 2017).

In the past 50 years, growth in demand for food has been met primarily by steady increases in agricultural productivity driven by the intensification of agricultural production supported by increased use of monoculture crops and an increasing reliance on chemical fertilizers and herbicides (Arneth et al., 2019). Since 1961, the total production of food (cereal crops) has increased by 240% (until 2017) because of land area expansion and increasing yields (IPCC, 2019). Continued productivity gains from these practices are now increasingly uncertain while antagonistic environmental impacts such as more intense competition for natural resources, increased greenhouse gas emissions, and further deforestation and land degradation are anticipated (FAO, 2017). The global rate of annual yield increase of cereal crops has steadily declined from 3.2% in 1960 to 1.5% in 2000 (FAO, 2009) while the initial impacts of climate change and global warming are already resulting in reducing yields in the most sensitive regions (Kornhuber et al., 2019). Consequently, new agricultural technologies that can reinvigorate productivity gains and enhance agricultural/food system efficiency are now critical to meet global food security goals. In the European Union (EU), the newly proposed EU Green Deal (EU, 2019) is an integral part of this EU Commission's strategy to implement the United Nation's 2030 Agenda and the sustainable development goals (UN, 2015). In addition to the productivity challenge, these proposals require EU food systems to become more transparent, continuing to supply healthy nutritious food from traceable production models, while simultaneously reducing environmental impact, supporting increased biodiversity and improved animal welfare, and reducing the use of hormones, agro-chemicals and antibiotics.

On that basis, the objective of this paper is firstly, to redefine the objectives and products of modern climate-smart dairy systems and secondly, in the particular case of temperate lowland grazing systems, to explore selected primary opportunities to realize these benefits within future systems. Although we do not exclude the application of these ideas to non-EU temperate regions, we acknowledge that our experience and perspectives are largely shaped by the EU context. We begin by outlining the contribution of intensively managed temperate grasslands to food production. We then discuss the demands of pasture-based systems on the dairy animal, and how these might be better addressed. We provide an overview of the potential contribution of multi-species grassland mixtures to nutrient efficiency and more sustainable grassland production. We conclude with a discussion of biodiversity and ecosystem services from dairy pastures, and the role of public and market-based payments to better incentivise the delivery of such services.

REDEFINING THE PROCESSES AND DESIRED PRODUCTS FROM CLIMATE SMART FOOD SYSTEMS

While the intensification and regional specialization of the Green Revolution in Agriculture during the last 60 years has greatly increased productivity, it has also resulted in adverse consequences for the natural environment. The continued intensification of such systems is now questioned in many developed economies worldwide. Firstly, the high reliance of intensive dairy systems on mineral fertilizer inputs has resulted in reduced nutrient use efficiency and an increased risk of nutrient losses to air and water. In addition, the increased use of concentrates, and in particular imported soya bean and palm kernel, creates increased demand for such crops in developing economies thereby stimulating deforestation and environmentally harmful agricultural practices elsewhere around the world. Allied to these damaging impacts of intensification, the loss of landscape biodiversity arising from such farming practices, combined with the disappearance of habitats for small land animals, insects or birds is also important in the context of the contribution of livestock farming to GHG emissions and global warming. In light of these criticisms, and in response to consumer demand for more environmentally sustainable food products, dairy systems must be adapted and redesigned to continue to provide sufficient high quality nutritious foods in addition to an

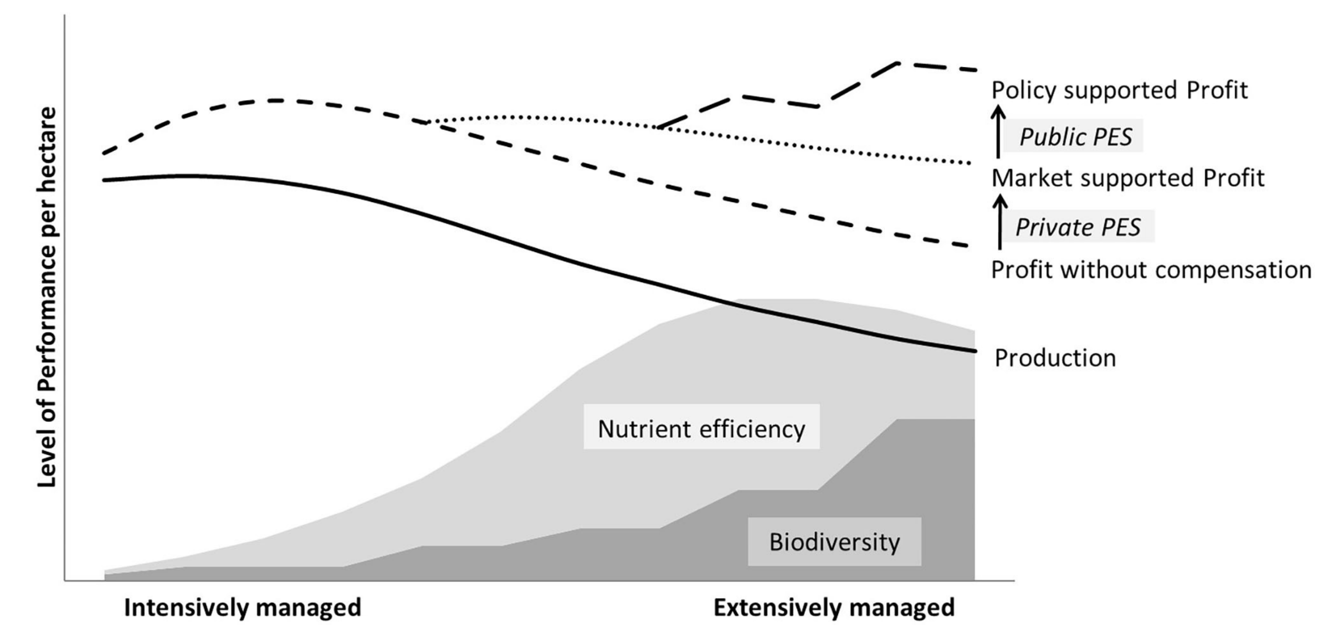

FIGURE 1 | Conceptual representation of farm scale input levels and output variables according to a gradient of management intensity from intensive to extensive. The various metrics relate to per unit area rather than per unit product. PES, payment for the provision of environmental public goods by various ecosystem services, see text for further details.

enhanced supply of ecosystem goods and services. This approach is conceptualized in **Figure 1**.

Although intensive dairy systems can achieve low levels of environmental impact when expressed per unit of product produced (Capper and Cady, 2020), the total level of environmental impact remains high when expressed per hectare of land farmed in more intensive systems while others aspects, which are poorly evaluated with the LCA approach, must also be considered (van der Werf et al., 2020). Therefore, as management intensity reduces, productivity per hectare or per animal will decrease and the reduction in per hectare productivity will occur commensurate with a reduction in environmental impact. Grassland nutrient use efficiency increases when inputs decrease, until an inflection when the low exportation rate results in a lower efficiency (Huguenin-Elie et al., 2018). Biodiversity mitigation in intensive systems is also difficult to achieve, with negligible increases in biodiversity until there is a major shift to more extensive practices (in a land sharing approach). For example, going from 250 kg ha^{-1} to 200 kg ha^{-1} of inorganic N fertilizer has negligible effects on grassland biodiversity, compared to going from 50 to 0 kg ha^{-1} (Kleijn et al., 2009). In essence, biodiversity conservation within dairy systems will only be achieved by protecting and improving the quality of adjoining wildlife habitats. For this reason, part of on-farm biodiversity enhancement can be achieved with relatively minor impact on production as the land areas most likely to be beneficial for biodiversity are likely to be those which are least suitable for dairy production e.g., areas of wetlands, woodlands, hedgerows, wet grasslands etc. Farm profitability (per hectare) will also reduce initially as productivity is reduced, however the reduction in profitability will at a lower rate than that for production. This is because the marginal profitability of extra production is lower for each additional unit of productivity within intensified systems due to increased marginal costs associated with intensification (Ramsbottom et al., 2015).

Finally, in our opinion, there is a non-linear relationship between production and profit and environmental impact according to the level of management intensity. A key challenge is to re-design farming systems so that required standards of environmental quality are delivered with least impact on production and farm profits. For the system to be robust, losses in income to the farmer arising from de-intensification should be compensated for providing a just transition to a new farming system. On that basis, the provision of environmental public goods should also result in enhanced market prices for producers of such products, either promoted by consumers' preferences ("Market supported" in **Figure 1**), or supported by public payments for the provision of public goods ("Policy supported" in **Figure 1**), or a combination of both. Such advanced market systems already occur in some countries such as Switzerland, France and Germany (see below).

THE EVOLVING ROLE OF LOWLAND TEMPERATE GRASSLAND IN FOOD SYSTEMS

Grasslands cover more than 40% of the earth land surface (excluding Greenland and Antartica) with a large diversity of vegetation (White et al., 2000). While grazing land is the single largest land-use category, the intensity of land use varies hugely within and among different land-use types, and regions with ∼10% of the total ice-free land surface managed intensively (Erb et al., 2016). A large part of the total grassland area is composed of native or natural grassland such as the savanna in Africa, the pampa in South America, shrub land and steppes in Oceania and Asia and tundra in Europe. Indeed, intensive and semi-intensive grasslands represent only a minor component (2%) of total land use (**Figure 2**; IPCC, 2019). Within the spectrum and context of future food systems, the specific case of temperate lowland grazing-based production is deserving of specific attention. In an EU context, improving the efficiency of grazing production systems is considered as the greatest opportunity to develop climate smart farming systems for the future.

In addition to forage production, grasslands play a major role in ecosystem equilibrium including biodiversity preservation, carbon storage, erosion control, water and nutrient cycling regulation (O'Mara, 2012; Soussana and Lemaire, 2014; Plantureux et al., 2016). In addition to the provision of these benefits, the role of grasslands in efficiently converting human inedible feed to high quality human nutrients has been acknowledged (Mottet et al., 2017; Peyraud, 2017). These systems are commonly practiced in temperate lowlands (such as Europe, New Zealand, and South America), are highly competitive and make a significant contribution to global food supplies. Similar to other food systems however, the intensification of grazing systems in the last 50 years using cheap mineral fertilizers and feed supplements has helped to increase management control and productivity in grazing systems. Consequently, today's pasture-based dairy systems can be described as semi-intensive or intensive systems with high levels of mineral nitrogen fertilizers, concentrates and irrigation applied to increase feed supply and reduce variability. In terms of feeding systems, they are increasingly specialized based on monocultures of sown grass or integrated in crop-livestock systems where grass and maize silage coexist (**Table 1**). Moreover, while grazing systems are widely recognized for the positive impacts on animal health and welfare (EU, 2009), the reduction in grazing season length, associated with the intensification of the EU dairy industry is now among the main animal welfare concerns for the sector (Nalon and Stevenson, 2019).

DESIGNING CLIMATE-SMART TEMPERATE GRAZING SYSTEMS

In the context of the desired evolution in climate-smart food systems (outlined in the previous section) we identify and discuss three pertinent issues for temperate lowland grazing systems. There are many others possibilities such as, for example, to better utilize the complementarity within integrated crops-livestock farming (Ryschawy et al., 2017), but we believe that the required increase in resilience and environmental benefits in temperate lowland grazing based dairy systems will be primarily based on the adaptation of livestock, feeding systems and ecosystem services. We discuss three specific changes

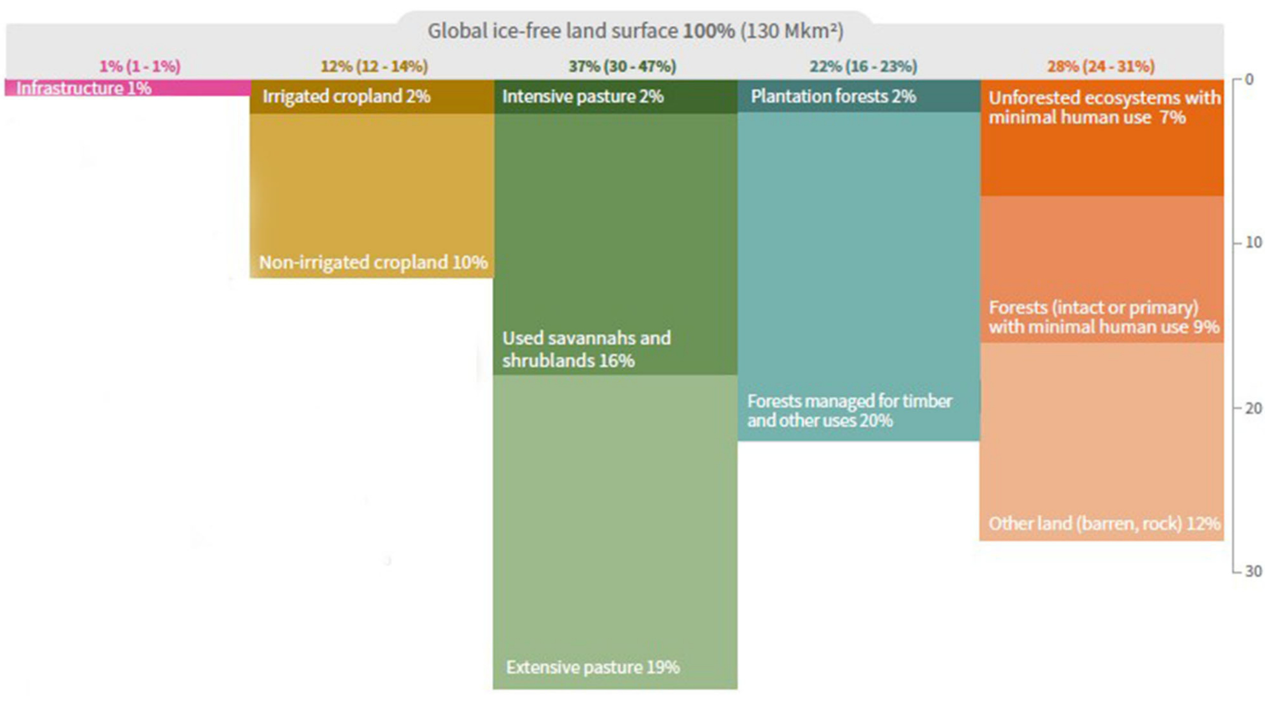

FIGURE 2 | Global, ice-free land area use 2015 (IPCC, 2019). (Each bar represents a broad land cover category; the numbers on top are the total percentage of the ice-free area covered, with uncertainty ranges in brackets and ordered along a gradient of decreasing land-use intensity from left to right).

TABLE 1 | Main characteristics of some pasture-based dairy systems in temperate lowlands (These data represent average values, and are derived from diverse national statistical publications).

	France	Ireland	Netherlands	New Zealand
Herd size (cows)	75	80	90	435
First lactation (%)	32	23	27	22
Milk yield (kg/cow)	7000	5000	8700	4200
Calving interval (days)	420	395	420	370
Concentrate (kg/cow)	1300	1000	2000	600
N mineral (kg/ha)	70	180	130	150
Grassland area (%)[a]	50	95	70	90
Forage crop area (%)[a]	50	5	30	10
Stocking rate (cow/ha)[a]	1.70	2.00	2.50	2.85

[a]*Calculated on the area used to feed the dairy cows.*

TABLE 2 | Dairy cows performance observed in the INRAE Le Pin experiment (The cow for the system?-2006–2019) and in the Teagasc NGH experiment (Next Generation Herd-2013–2016) in comparison with the objective for grass-based dairy system and compact calving management (12 weeks calving period).

	Objective	The cow for the system?[a]				NGH[b]	
Breed		**Holstein**		**Normande**		**NatAv**	**Elite**
Feeding level		**High**	**Low**	**High**	**Low**		
Milk yield (kg)		8360	6000	6200	4625	5810	5610
Milk solids (kg)		568	411	457	342	451	459
BCS at calving [pts (0–5)]		2.80	2.65	3.40	3.05	3.00	3.25
BCS losses [pts(0–5)]	−0.50	−0.90	−1.15	−0.60	−0.80	−0.40	−0.40
Interval calving−1st ovulation (days)	25–30	41	39	33	30	/	/
Normal cyclicity profile rate (%)	80	51	43	67	76	/	/
First AI in-calf rate (%)	60	36	29	43	41	46	60
6 week in-calf rate (%)	70	40	36	49	52	58	73
13 week in-calf rate (%)	90	60	56	73	70	83	93

[a]*High: In winter (100 days), early in lactation, total mixed ration with maize silage, dehydrated alfalfa, and concentrate, ad libitum. At grazing (180 days), 0.35 ha per cow, 4 kg concentrate, and 5 kg maize silage from July. In autumn (85 days), 5 kg maize silage, 4 kg concentrate, and grass silage ad libitum.*
Low: In winter (100 days), early in lactation, total mixed ration with grass silage, and big bale haylage, ad libitum. At grazing (180 days), 0.55 ha per cow. In autumn (85 days), grass silage ad libitum. No concentrate. (updated from Delaby et al., 2018).
[b]*Two genotypes based on Ireland's dairy selection index, the Economic Breeding Index (EBI): NatAv (n = 45 annually) representing national average based on EBI and Elite (n = 90 annually) representing the top 1% (O'Sullivan et al., 2019, 2020).*

to farm practices namely; the selection of cows adapted to grazing, the development of multi-species pastures and the promotion of biodiversity and associated ecosystem services through semi-natural habitats.

MATCHING THE COW TO THE SYSTEM

In livestock farming systems, the animal is a key component of an efficiently working system. In low-input, pasture-based systems, more than others, the dairy cow is a feed-to-food transformer, converting grass to milk. In these systems, increasing the proportion of grazed grass in the annual feeding budget reduces total costs and increases farm returns (Ramsbottom et al., 2015). Consequently, the dairy cow must possess critical attributes, which are associated with the particularities of the grass-based systems of production.

In grazed grass-based systems, three main aspects should be highlighted to define the "ideal" animal. By construction, the feeding resource is based on forages defined with a higher fill value and a lower energy nutritive value than concentrate based feeding. Secondly, to manage grazing with high efficiency and a low post grazing residual height, the grass offered restricts the expression of the animal intake capacity. Finally, this resource is naturally seasonal, unstable, and uncertain with huge variation in feed supply due to the sensitivity to climate variation.

The first consequence, resulting from the two first specifications of the grazed based system is the failure to fully meet the nutritional requirements of high genetic merit dairy cattle for milk yield within a grass only diet. This is illustrated by Bargo et al. (2002) with their experiment comparing indoor and grazing feeding systems. The total daily dry matter intake, milk yield and milk solids were lower (−5.1, −9.6, and −0.69 kg, respectively) for grazing dairy cows. With such high demands for energy and protein, due to the continental Holstein milk yield potential, grass intake is unable to satisfy completely the mammary gland requirements. In this situation, although the grass nutritive value (energy, protein content) is high, the overall level of intake achieved is inadequate. With genetic selection based mainly on milk yield, the dairy cow intake capacity increases but much less than the associated energy demand. Consequently, at grazing without supplementation, high genetic merit cows are unable to express their potential due to the form and nature of the forage offered. In the same way, in farmlet experiments comparing different types of cows managed at different feeding levels, the authors often report a phenotypic interaction on total milk and milk solids yield (Horan et al., 2005; Fulkerson et al., 2008). Comparing animal performance, typically, the greater the milk yield or milk solids potential of the cow, the greater the difference observed between high and low feeding treatments at grazing. Indeed, the milk production response to feeding level of high genetic merit cows is generally higher than for dual-purpose, crossbred, and lower genetic merit cows (**Table 2**; Delaby et al., 2014). Continuing to select on milk yield potential will lead to a nutritional impasse.

The final characteristics of grazed based production systems, associated with the seasonality of grass growth, has two main consequences in terms of herd management and animal robustness. The dairy farmers are highly motivated to synchronize herd demand with grass availability using compact calving in spring to maximize grass utilization (Delaby and Horan, 2017). In environments where a period of drought is probable during summer for example, and without irrigation or with severe restriction on water utilization, Pottier et al. (2007) have suggested keeping compact calving management but with two compact calving periods at 6-month intervals is appropriate.

In this situation, half of the herd demand is associated with dry cows, in summer or in winter, the traditional period with reduced pasture growth. Two periods of compact calving can allow total feed requirements to be reduced on the grazing platform thereby allowing available pasture and the best-conserved forages to be dedicated to the milking cows during periods of feed restriction.

To obtain compact calving at the same time every year requires compact rebreeding before day 90 of lactation. For dairy cows, this period is early in lactation and concomitant with the peak of lactation. Due to the gap between intake and energy demand, increased peak milk production results in increased body reserve mobilization resulting in a reduced likelihood of successful timely rebreeding (Butler, 2014; Bedere et al., 2016, 2017). Typically, continental Holstein dairy cows are unable to conceive within the required short timeframe due to high milk production levels which are detrimental to the maintenance of adequate body condition to facilitate conception at the right moment and avoid ill health within a restricted feed environment (**Table 2**; Baumont et al., 2014; Delaby and Fiorelli, 2014). Consequently, a more appropriately balanced (milk plus fertility potential) dual purpose or cross breed cow with lower milk production and superior fertility is beneficial to maintain high fertility capacity which is essential for grazed grass based dairy systems (Washburn and Mullen, 2014). This has been done with success in Ireland. Starting 20 years ago, the definition and the application of an Economic Breeding Index has paid dividend (Berry et al., 2019). In comparison with national average genetic merit cattle, the performance of high EBI dairy cows in terms of milk yield, milk composition, and fertility are consistent with the ambition of this program (**Table 2**; O'Sullivan et al., 2019, 2020).

In the future, two or three main aspects must be kept in mind to further improve the animal capability to assume better grass based systems constraints. Firstly, in relation to animal health and welfare, selecting for a healthier cow will be the first step to improve animal welfare. Specifically at grazing, the selection of animals, which are resistant to lameness and parasitism to limit use of antibiotics and anthelmintic products, is an opportunity for the future. Some breeds such as Normande or Montbéliarde dairy cows are more sensitive than Holstein or Jersey or Kiwi-cross breeds to lameness, probably because of high animal bodyweight and hoof hardness which is underdeveloped for long walking distances. Resistance to parasitism is important for heifers during the first grazing season and it is well-known that parasitism sensitivity differs between animals and is heritable. In fact, some specific approaches based on selective anthelminthic treatment using standard growth curves and regular animal weighing must be further developed to reduce use and limit the anthelmintic footprint of food production in addition to the risk of anthelmintic resistance (Delaby, 2015). Such approaches to limit anthelminthic treatment must be further developed for the future.

A second concern for the future is the potential for more erratic grass growth patterns, as anticipated climate change will increase the frequency of negative hazards. The reduction in inorganic nitrogen fertilization and the control of water use for irrigation will also make the system more dependent on the natural processes of mineralisation and fixation. That may also contribute to increase pasture supply variability in future. Such system changes coupled with the increasing frequencies of unpredictable weather events will exacerbate the volatility of pasture supply and nutritive value (Lee et al., 2013), and will require future dairy cattle that can withstand periods of nutritional restriction. The ideal dairy cow should have the inherent capability to reduce milk yield during periods of restriction, to protect vital processes and thereafter, to rebound when forage supply recovers. To select on this capability, named plasticity (Friggens and Newbold, 2007), a methodology has to be developed to challenge the animal and observe their reactivity. In the short term, we know that the dairy cow is able to reduce milk yield during short term feed restrictions and preserve the mammary gland secretion potential. This is illustrated well with the milk yield profile observed in long residence time rotational grazing paddocks when grass availability declines between the first and the last day in the paddock (Roca-Fernandez et al., 2012). In the longer-term, this capability to recover mammary gland milk synthesis potential is modest and the carry over effect will depend mainly of the duration and severity of the restrictive feeding period, the dairy cow milk production potential and body reserves (Delaby et al., 2009).

Finally, as an integrative property, a well-adapted dairy cow for future grass based systems is a cow with greater longevity. Farmers describe *"a transparent cow, a cow you never hear about"* (Delaby et al., 2018). This cow is able to be in calf at the right moment, with no or few health problems, and produce high fat and protein content milk according to the feeding level available from grazed grass. In this situation, the replacement rate is low which helps to reduce environmental impacts such as the global GHG emissions of the dairy system (Dall-Orsoletta et al., 2019). In the same direction, reduced inorganic nitrogen use facilitated by the (re)introduction of legumes into pastures will also reduce GHG emissions and increase N efficiency. Improving the global efficiency of the system, with higher dairy cow durability will generally have a simultaneous positive effect on the environment.

MULTI-SPECIES MIXTURES: BENEFITS OF DIVERSITY

There has been renewed focus on the incorporation of legumes into intensive grassland-livestock systems. A well-managed legume proportion in a sown grassland (ideally 30–50% legume content) can result in higher productivity and reduced production costs (Suter et al., 2015). These savings are achieved through lower reliance on inorganic nitrogen (N) fertilizer, a prominent variable cost in intensive dairy systems. In Switzerland, grass-legume mixtures receiving 150 kg ha^{-1} yr^{-1} of N fertilizer out-yielded grass monoculture receiving 450 kg ha^{-1} yr^{-1} of N fertilizer when legume proportion comprised 30% or more of the vegetation biomass (Nyfeler et al., 2009). In a continental-scale experiment, four-species mixtures (two grasses and two legumes) consistently yielded better than the average of the four monocultures, and even yielded more than the best-performing monoculture in a majority of cases (Finn et al., 2013). Grange et al. (2019) also showed that combining competitive grass, legumes and forbs (with 150 kg ha^{-1} yr^{-1} of N fertilizer) achieved a fertilizer replacement value sufficient to out-yield a perennial ryegrass monoculture with 300 kg ha^{-1} yr^{-1} of nitrogen.

Better nitrogen fertilizer use efficiency is associated with higher forage nitrogen content, thus, incorporating legumes can bring higher milk solids from a lower-input system (Harris et al., 1997; Egan et al., 2015). In addition, the inclusion of forbs in a grass-legume sward can bring extra yield and more complete feeding value, especially of minerals and bioactive secondary metabolites (Delagarde et al., 2014; Cranston et al., 2015; Cong et al., 2016). Despite the technical difficulty in quantifying the benefit of these metabolites in livestock health, we know that several husbandry pathologies can be tackled by a diverse diet that includes high concentrations in some of these metabolites (Poutaraud et al., 2017). In an example that differentiated grass and/or clover effects from grass+clover+herb vegetation, a 2-year study investigated lamb and ewe performance on perennial ryegrass only, perennial ryegrass and white clover, and a six-species and nine-species mixture. Lambs on the six-species mixture had heavier bodyweights and required fewer anthelmintic treatments than lambs grazing either perennial ryegrass or perennial ryegrass and white clover. Lambs grazing the perennial ryegrass sward required more days to reach slaughter weight than lambs grazing all other sward types (Grace et al., 2019).

On a broader scale, by diversifying plant species, we reduce the risk of deficiency in any aspect of an animal diet. To illustrate this in a 2-year grazing experiment (with 75 kg N ha^{-1} yr^{-1}) in France, an increase of botanical complexity from one to five species (two grasses, two clovers, and chicory) resulted in positive effects on animal performance (Roca-Fernández et al., 2016). They distinguished between monocultures of perennial ryegrass, grass-clover mixture, and "multi-species swards" of grasses, clovers, and chicory. Compared to grass-clover, multi-species swards improved production of milk (+0.8 kg/day) and milk solids (+0.04 kg/day), which was attributed to enhanced sward quality and increased dry matter intake (+1.5 kg DM/day). Compared to monocultures, plant richness also enhances grassland stability over seasons and weather disturbances. As climate change is leading to more extreme weather events such as summer drought (Hopkins and Del Prado, 2007), multi-species swards have shown better resistance than monocultures in several studies (Vogel et al., 2012; Isbell et al., 2015; Craven et al., 2016; Finn et al., 2018). When including forbs, multi-species swards contributed to increase carbon sequestration (Cong et al., 2014). Mixtures are also very stable against weed invasion which is another threat in intensive dairy systems (Connolly et al., 2018), and facilitates a reduced reliance on herbicides. In summary, increasing plant diversity in sown grasslands (to levels with four to eight selected species) is an example where better environmental performance can be achieved without any reduction in productivity, even when there is a reduction in farm inputs (Weigelt et al., 2009). In an economic analysis, (Schaub et al., 2020) found higher farm profitability and reduced production risk from multi-species grassland compared to a monoculture.

BIODIVERSITY AND ECOSYSTEM SERVICE PROVISION

Globally, there is an ongoing decline in both biodiversity and the provision of ecosystem services. Much of European biodiversity is associated with extensively managed farmland; agricultural intensification is a major driver of this decline through conversion (e.g., species-rich grassland or woodland is converted to cropland or forestry), fragmentation, homogenisation, and modification (overgrazing, undergrazing, and the application of nutrients and biocides) of habitats. Intensively managed farming systems, therefore, prioritize the delivery of selected provisioning services (food), at the expense of land uses that are favorable for biodiversity, and associated ecosystem services. Thus, it is perhaps not surprising that surveys of intensively managed farms show that most of the original farmland habitats have been removed, and there tends to be only small habitat fragments remaining. For example, farmland habitats in a survey of mostly grassland farms in Ireland reported semi-natural habitat areas of 14 and 13% (Sheridan et al., 2011, 2017); Sullivan et al. (2011) reported an average of 15%. In an Irish study of more intensively managed farms ($n = 119$), the wildlife habitat area across three separate farming enterprises (tillage, beef, and dairy) comprised almost 10% of the farm area. Linear features such as hedgerows, buffer strips and drainage ditches accounted for 43% of the total area of wildlife habitat surveyed, and hedgerows were the single most abundant wildlife habitat (Larkin et al., 2019). Looking at a gradient of farming intensity from extensive to intermediate to intensive, the Farm Ecos project in Ireland showed that the area of semi-natural habitat was 42% to 15.6% to 6.1%, respectively (Rotchés-Ribalta et al., 2020). Overall, these studies demonstrate how intensive agricultural management such as occurs on most dairy systems is generally associated with a reduced area of habitat available for wild populations of plants and animals, and especially when there is low protection afforded to habitats by policy (Rotchés-Ribalta et al., 2020). There is also a wider off-farm impact of livestock systems that may not be captured by farm-scale metrics e.g., biodiversity impacts that arise from conversion of tropical rainforest for cultivation of soy to supplement animal intake of protein, and biodiversity impacts from downstream impacts on water quantity. Importantly, the off-farm biodiversity impacts due to land use change can be as large as those that occur on-farm (Teillard et al., 2016); the greater the reliance on off-farm feed, the greater the impact. Methods to better assess the impact of livestock systems are under development (FAO, 2020).

There is a growing expectation from society for agricultural systems to improve their environmental sustainability, and to respond to the climate and biodiversity crises. Food production systems vary widely in their environmental sustainability, and the public perception of food production has become increasingly polarized.

What role can lower-input pasture-based dairy systems play to improve biodiversity? Some general guidance for habitat triage follows:

- Protect and maintain the appropriate management of existing natural habitats that support wild populations of plants and

animals e.g., ponds, hedgerows, native woodland, peatlands, wetlands, heathlands etc.
- Enhance the wildlife quality of degraded farmland habitats through improved management.
- Only consider the creation of new wildlife habitats after existing habitats have been retained or enhanced.
- Do not locate newly created wildlife habitats on existing habitats.

In practice, within dairy systems, likely actions will include: protection and conservation of existing habitats with native vegetation and species; planting of new hedgerows; improved management of hedgerows to support more wildlife; widening of existing field margins; creation of field margins; creation of ponds and planting of small woodland areas. Excessive cutting and management of hedgerows removes flowers and food that supports a variety of invertebrate species (including pollinator species) and can destroy over-wintering insects. More appropriate management of hedgerows for wildlife involves trimming on rotation every second or third year. An example of a project undertaking demonstration of such actions is taking place in the Bride Valley, Cork, Ireland (BRIDE project www.thebrideproject.ie).

The benefits of such actions extend beyond the improvement in allocation of space for biodiversity. For example, for hedgerows and wooded areas (that are characteristic of many temperate landscapes in Ireland, and bocage in France), wider benefits include:

- Shelter and shade. Hedgerows and trees provide shelter from winds and cold weather. In addition, they also provide shade and protection from heat stress during warmer weather and heatwaves. The physical barrier provided by thick hedges contributes to reduced disease transmission among herds.
- Carbon sequestration. Hedgerows can also contribute to carbon sequestration: the greater the volume and age of the hedgerow, the more carbon is likely to be sequestered.
- Improved water infiltration. Water infiltration is higher adjacent to hedges, and can prevent lameness due to foot-splaying and is less suitable to snails that are hosts to liver fluke.
- Improved pollination services. The diversity of plants and floral resources in diverse hedgerows provides habitat and food for wild pollinating insects. These will benefit adjacent crops that are pollination-dependent, as well as contributing to biodiversity.
- Biological control. Habitat diversity underpins the diversity of species that naturally contribute to the control of agricultural pests and diseases, and reduces the reliance on chemical methods of control.
- Landscape connectivity.

MARKET AND POLICY ACTIONS TO ENHANCE BIODIVERSITY AND ECOSYSTEM SERVICES

A number of possible market and policy actions are available to curb the greatest impacts of production systems, but also to actively enhance their positive contributions. In considering what unique role exists for lower-input dairy systems to improve biodiversity, some examples include:

- Voluntary actions by farmers. These are highly dependent on personal motivation, and availability of good advice for environmental management and biodiversity conservation. We do not discuss this any further here.
- Entry-level criteria that are associated with market access.
- Public payments for environmental public goods. Here, we give an example based on EU agri-environment schemes, and discuss recent developments that focus on results-based approaches and payments.
- Private initiatives/market-based incentives to reward provision of ecosystem services. We provide two case studies here.

Agri-food companies are undertaking sustainability assessments for compliance or benchmarking with international accreditation schemes. Increasingly, food processors are requesting that suppliers (farmers) attain minimum criteria as a condition of supply to the processor. In general, such approaches tend not to be very demanding, and are highly dependent on adequate compliance inspection and availability of adequate advice. In addition, such approaches tend to be more suited to preventing future impacts rather than restoring ecosystems that were impacted in the past. As one example of an international accreditation scheme, the Sustainability Assessment Initiative (SAI) Platform is a global initiative, and includes several biodiversity criteria (essential, basic, and advanced) in its Farm Sustainability Assessment (FSA) tool (www.saiplatform.org).

In the EU, the Common Agricultural Policy is an extremely prominent policy, and key instruments include: income support through direct payments that ensure income stability, and remunerate farmers for environmentally friendly farming and delivering public goods; market measures to deal with difficult market situations, and; rural development measures with national and regional programmes to address the specific needs and challenges facing rural areas. Within the Rural Development Programme, agri-environment schemes are intended to be a major contributor toward CAP objectives to reverse biodiversity decline and restore ecosystem services, improve good water quality and mitigate climate change impacts of food production. In the European Union, the primary source of funding for biodiversity conservation and ecosystem services now derives from agri-environment policies (reflecting the large relative size of the CAP to national and other funds for biodiversity conservation). In practice, the administrative workload and payment levels from agri-environment schemes are not sufficiently attractive for most dairy farmers, and they tend to have low participation levels in biodiversity actions as part of agri-environment schemes.

It is clear, however, that the business-as-usual, "one-size-fits-all" EU approach that has been characteristic of most agri-environment schemes has failed to deliver the best biodiversity and ecosystem services outcomes, despite their considerable financial costs. There is a general acceptance among researchers and policymakers that agri-environment schemes need to be more focussed and better targeted to deliver verifiable results (ECA, 2011). In line with this expectation, a novel approach for the development of such schemes is to incorporate "results-based approaches" and payments. Results-based approaches tend to define an objective, and then offer a payment that is related to the degree to which the objective has been attained (see O'Rourke and Finn, 2020). This is in contrast to "action-based approaches" in which the service provider is provided with a standard payment that reflects the transaction costs and income foregone for undertaking an action–importantly, this payment is independent of the outcome that is achieved (**Figure 3**).

This approach is most likely for a high-quality environmental outcome that is in demand and targeted by policy (e.g., protection of species-rich grasslands). In typical action-based approaches (a), the payment rate (y axis) is standard (represented by the horizontal dashed line in the left panel) despite the large variation in the delivery of the ecosystem service represented by the distribution of points. In an example from results-based approaches (b), the exact same level of performance is supplied from the same farms in the left panel, but the payment rate is related to the level of supply of the ecosystem service: the higher the level of supply, the higher the payment. In this example, there is a threshold level of quality below which a low or no payment is made. In this scenario, some farms do not receive a results-based payment. From a scheme perspective, this may represent a form of targeting; however, these farms may participate in other more relevant schemes, or may receive non-productive investments that allow them to increase their score over time and then be eligible to receive payments. Looking to the future, such more targeted approaches may better attract dairying systems to participate in approaches that aim to improve specific environmental objectives. A good example of such an environmental objective would be carbon conservation on farmland. This could (1) reward farmers for continuing farming practices that protect existing stocks of carbon on farmland and grassland (e.g., conservation of permanent grassland, continuation of carbon-conserving practices and protection of hedges and woodland) and (2) incentivise practices that increase carbon sequestration where it is considered to be a scientifically valid opportunity (e.g., conversion of tillage to permanent grassland, adoption of carbon-conserving practices to increase C sequestration on grassland, planting of woody vegetation).

PAYMENT FOR ECOSYSTEM SERVICES: POTENTIAL FOR PUBLIC-PRIVATE PARTNERSHIPS

The emergence of public-private partnerships for the provision of environmental public goods is one of the innovations that may arise through up-scaling of results-based approaches. To date, the prevailing view about agri-environment schemes has been dominated by the provision of environmental public goods being delivered through public payments from the national (or international) taxpayer. Such efforts were originally required because of market failure to internalize the negative/positive impacts of some types of production systems. The growing market awareness and reliance of food brands on sustainability standards represents an effort to internalize the environmental benefits of farming systems i.e., brands want to be associated with practices that are good for soil, water, climate and biodiversity (among other attributes). However, with this internalization of the reputational benefits of sustainability standards also comes with it the possibility of internalization of the costs of achieving these sustainability standards. Might we see greater interest in public-private partnerships that result in some combination of public and private payments for environmental goods and services? If so, it is difficult to see such an approach that would not involve clear and verifiable delivery of the stated standards. Therefore, results-based approaches (see **Figure 3B**) have a strong role in the delivery of public-private partnerships for delivery of ecosystem services. There are some examples of

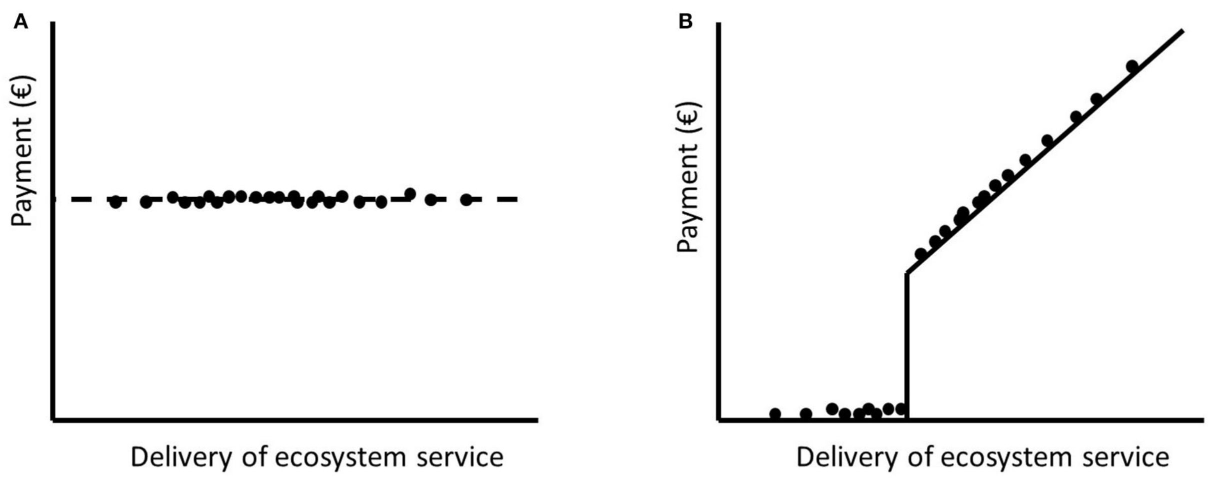

FIGURE 3 | Comparison in the distribution of payments in relation to level of outcome in **(A)** action-based approaches and **(B)** results-based approaches (adapted from O'Rourke and Finn, 2020).

this across Europe e.g., Pro Weideland programme in Germany, and TerraSuisse in Switzerland.

The Pro Weideland programme promotes grazing as nature-oriented husbandry, with its positive influences on environmental protection, animal welfare, and biodiversity. What is especially interesting about the Pro Weideland example is its market-facing approach, and its governance structure. The initiative arose out of a stakeholder-based response to consumer demands for dairy systems that are better for the environment and animal welfare. Farmers receive a premium for their milk that is determined (and paid) by the processor, and varies from one to four cent (€ currency) per liter, depending on the different participating co-operatives. In 2020, about 1,500 farmers participate in the PW programme (and this number is growing). The label is supported by strict standards, a legal entity to manage the programme, and independent monitoring of the procedures and implementation.

The Swiss organization for integrated farming (IP-Suisse) comprises about one quarter of Swiss farmland. In 2009, IP-Suisse incorporated a Credit Points System (CPS) in their production guidelines. Based on expert knowledge, the CPS is a predictive tool that includes farmers' efforts for biodiversity on the farm, and allocates points for management practices that increase the wildlife value of farmland. The scores are correlated with biodiversity (Jenny et al., 2013), and producers associated with IP-Suisse have to reach a defined point score. Produce from IP-Suisse farmers are sold by the large Swiss retailer Migros under the "TerraSuisse" label. In addition to the state-funded environmental payments for ECAs, farmers also receive a payment from Migros (Jenny et al., 2013). Importantly, the TerraSuisse approach and related initiatives also enhance the public perception of farming and farmers. This is also a good example of a public-private partnership in which the TerraSuisse approach uses market instruments to add (financial and biodiversity) value to the federal public payments for ecological compensation areas.

CONCLUSION

Pasture-based systems have many positive aspects in their production of healthy food from livestock fed on grassland forage, which is not directly utilizable as food by humans. This is well-known and recognized by consumers. However, over the last 50 years of intensification, increased stocking rates and associated agrichemical inputs have resulted in multiple environmental impacts. In temperate areas, there is a questionable reliance on systems that are dominated by perennial ryegrass monocultures supported with high levels of inorganic fertilization, the removal of hedges and drainage ditches to facilitate grazing and mechanization, and increasing use of concentrates in dairy feeding. As food demand increases, consumers want to know more about the production system both in terms of the environmental impact and the welfare of animals. We highlight an opportunity for pasture-based systems to be more consistent with societal demands, and to transform this demand into success. This challenges animal science to develop a type of cow that is well-adapted, robust, and appropriate for the system. Multispecies pastures are one practical farm-scale response to questions around nutrient use efficiency, feed self-sufficiency and forage quality, biodiversity, and long-term C sequestration. On the periphery of the grazing platform, the presence and appropriate management of hedgerows can increase the contribution to biodiversity, and promote ecological habitats and niches. These positive practices contribute to a de-intensification of the dairy system, and will partially change the objectives for breeders of both livestock and forage plants. Consequently, this contribution of livestock farming to ecosystem services has to be recognized by consumers and society. Moreover, different forms of payments for ecosystem services need to be developed that target and incentivize positive characteristics. To achieve this successful transition, financial signals from the marketplace can help in addition to agricultural policy supports to encourage the change that is desired by consumers and society, is equitable to farmers and consistent with the goals of sustainable farming.

AUTHOR CONTRIBUTIONS

This review has been co-written by the 4 co-authors. After a one-day meeting together in Ireland to define the overall plan and divide the sections, each author has made a contribution to the text. BH: the Introduction. BH and LD: the chapter The Evolving Role of Lowland Temperate Grassland in Food Systems, Designing Climate-Smart Temperate Grazing Systems, and Matching the Cow to the System. GG: the chapter Multi-Species Mixtures: Benefits of Diversity. JF and GG: the chapter Biodiversity and Ecosystem Service Provision. JF: the chapter Market and Policy Actions to Enhance Biodiversity and Ecosystem Services and Payment for Ecosystems Services: Potential for Public-Private Partnerships. LD: the Conclusion. These different parts have been combined and a 2nd meeting organized to finalize and revise the combined draft. All authors contributed to the article and approved the submitted version.

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frontiers in Sustainable Food Systems

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Native Grasslands at the Core: A New Paradigm of Intensification for the *Campos* of Southern South America to Increase Economic and Environmental Sustainability

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Extensive livestock production in southern South America occupies ~0.5 M km^2 in central-eastern Argentina, Uruguay and southern Brazil. These systems have been sustained for more than 300 years by year-long grazing of the highly biodiverse native Campos ecosystems that provides many valuable additional ecosystem services. However, their low productivity (~70 kg liveweight/ha per year), at least relative to values recorded in experiments and by best farmers, has been driving continued land use conversion towards agriculture and forestry. Therefore, there is a pressing need for usable, cost effective technological options based on scientific knowledge that increase profitability while supporting the conservation of native grasslands. In the early 2000s, existing knowledge was synthesized in a path of six sequential steps of increasing intensification. Even though higher productivity underlined that path, it was recognized that trade-offs would occur, with increases in productivity being concomitant to reductions in diversity, resilience to droughts, and a higher exposure to financial risks. Here, we put forward a proposal to shift the current paradigm away from a linear sequence and toward a flexible dashboard of intensification options to be implemented in defined modules within a farm whose aims are (i) to maintain native grasslands as the main feed source, and (ii) ameliorate its two major productive drawbacks: marked seasonality and relatively rapid loss of low nutritive value-hence the title "native grasslands at the core." At its center, the proposal highlights a key role for optimal grazing management of native grasslands to increase productivity and resilience while maintaining low system wide costs and financial risk, but acknowledges that achieving the required spatio-temporal control of grazing intensity requires using (a portfolio of) complementary, synergistic intensification options. We sum up experimental evidence and case studies supporting the hypothesis that integrating intensification options increases both profitability and environmental sustainability of livestock production in Campos ecosystems.

Keywords: livestock, adaptative management, intensification options, South America, Pampa biome, grassland management

INTRODUCTION

Global and Regional Context of Agricultural Intensification

In the last 20 years, agricultural production has increased in most regions of the world through improving yields and through the expansion of the cultivated land area, typically at the expense of natural habitats (Burney et al., 2010). As a result, food production per capita is today 22% higher than 20 years ago (FAOSTAT, 2019). The world population and food consumption per capita have also increased in the last 20 years, by 30 and 8%, respectively (FAOSTAT, 2019). These trends are expected to continue in the foreseeable future with an increasing demand for animal protein for human consumption.

In this context, it is unlikely that extensification would suffice to cover such demands without major negative environmental effects. Land degradation is already extensive, affecting 23% of the world's terrestrial area and 1.5 billion people globally, and increases by 5–10 million ha year^{-1} (Munir et al., 2017). Conversely, there is room for moderate intensification of under-yielding agricultural systems so that increases in production are made with known and controlled environmental impact (Tilman et al., 2011). However, this path of moderate intensification requires a solid knowledge of the multiple trade-offs operating between agricultural output and other environmental services in these agroecosystems.

The South American *Campos* is an ecological region that extends over 0.5 M km^2, between 27° S and 35° S in central-eastern Argentina, Uruguay, and southern Brazil (**Figure 1**). It is dominated by spatially heterogeneous temperate and subtropical grasslands conformed by a complex mosaic of species assemblages related to soil types and grazing intensity (Berretta et al., 2000). Average annual temperature in Campos region varies from 16.6°C in southern Uruguay to 21.1°C in the northern Corrientes, while the average annual rainfall varies from 1,000 mm in southern Uruguay to 1,600 mm in the northern Campos in Brazil (https://en.climate-data.org/south-america/).

Campos ecosystems are mainly used for extensive livestock production but also provide a range of valuable ecosystem services that affect human well-being (Viglizzo and Frank, 2006; Weyland et al., 2017). Such ecosystem services include the sustenance of plant and animal biodiversity (4,864 plant species: Andrade et al., 2018; 385 bird species and 90 mammal species: Bilenca and Miñarro, 2004), control of soil erosion and storage of soil organic carbon, nutrient cycle regulation and water provision (Costanza et al., 1997; Chalar et al., 2017), climate regulation as well as providing scenic beauty, culture, and livelihood for local rural residents (Costanza et al., 1997). These high-diversity and unique grasslands may also be used as a source to improve biochemical richness of meat and milk, as well as environmental health, as it was hypothesized by Provenza et al. (2019). However, these species-rich grasslands are being threatened by changes in

FIGURE 1 | The Campos ecosystem of South America. It includes the South and North grasslands of Uruguay, Pampa biome of south Brazil, and central-eastern grasslands of Argentina.

the land use (Overbeck et al., 2007), and strategies are needed to improve livestock production in synergy with ecosystem conservation (Carvalho and Batello, 2009).

Agroecosystems based on the use of *Campos* grasslands have been managed extensively for livestock production for more than 300 years with negligible use of external inputs (Viglizzo et al., 2001), and thus often show relatively high environmental sustainability (Viglizzo and Frank, 2006; Blumetto et al., 2019). However, very few farms are capable of combining this with high productivity and profitability, and indeed most farms present large yield gaps relative to the productive potential (Modernel et al., 2018). Therefore, the area of native *Campos* ecosystems has been declining since the 1970s due to conversion to grain crops, cultivated pastures, and forestry plantations (Viglizzo and Frank, 2006; Baeza and Paruelo, 2020). Today, remnant native grasslands occupy 36% of their original extension in Rio Grande do Sul-Brazil (Trindade et al., 2018), 64% in Uruguay (Cortelezzi and Mondelli, 2014), and 26% in Entre Ríos and 72% in Corrientes in Argentina (INDEC, 2018).

Thus, in these non-subsidized economies that do not pay for the ecosystem services and have very few specific instruments to regulate the conservation of native grasslands, low comparative profitability of extensive livestock production is driving a sustained process of land-use change based on the replacement of native *Campos* grasslands. Lack of profitability leads to above-optimal stocking rates, particularly in small farms, which gives place to a vicious cycle of degradation and consequent low productivity and even lower profitability (Tiscornia et al., 2019). The challenge is to devise strategies of intensification that increase profitability while maintaining the native *Campos* grasslands as a main feed source for livestock, so that higher productivity can be reconciled with the maintenance or improvement of all other services provided by these agroecosystems as proposed by Dumont et al. (2018).

PORTFOLIO OF LIVESTOCK INTENSIFICATION IN *CAMPOS* ECOSYSTEM

Livestock production systems based in *Campos* ecosystems are characterized by year-round grazing at relatively constant stocking rates (Royo Pallares et al., 2005). Native grasslands mean primary production range from 2900 to 6300 kg DM ha^{-1} year^{-1} (Berretta et al., 2000; Bendersky et al., 2017) and mean secondary production 60–70 kg liveweight ha^{-1} year^{-1} (Carvalho et al., 2006). The primary productivity and nutritional value of these grasslands show large seasonal variations, with minimal values in the winter period due to the decrease in temperature and solar radiation and the predominance of C4 grasses. Indeed, a large proportion of the annual production of native grasslands is concentrated over a few spring and summer months (Berretta et al., 2000). Imposed over this seasonality, inter-annual variation is mainly related to rainfall variability (Cruz et al., 2014; Guido et al., 2014). Under these conditions, grasslands become recurrently overgrazed in periods of low forage production, a situation that becomes particularly aggravated during the severe droughts that occur every 10 years or so. In order to overcome these constraints, several intensification options are available and have been assessed in these systems.

Process-Based Technologies

Stocking Rate Management

The control of grazing intensity through the management of stocking rates is a key tool to adjust the forage offered to animals in livestock systems. A few long-term set stocking experiments were implemented in the *Campos* ecosystem in order to determine stocking rates that maximize individual and per area productivity, so that general recommendations can be given to farmers (Royo Pallares et al., 1986). However, due to high soil and climatic variability, the results of these experiments were useful only to set general guidelines to set stocking rates. A long-term experiment aimed at describing the quadratic relationship between forage on offer and animal liveweight gain using short-term stocking rate adjustment (Mott, 1960) indicated that productivity was optimized at 8% of forage on offer (Maraschin et al., 1997).

Forage on offer affects standing forage mass and therefore forage growth (Soares et al., 2005), forage intake (Da Trindade et al., 2016), and energy partitioning (Do Carmo et al., 2016). In order to implement this practice, monitoring forage production and animal liveweight is a prerequisite for regulating plant-animal relationship. Monitoring frequency depends mainly on pasture growth rates and management and business decisions. In cow-calf experiments, Claramunt et al. (2018) and Do Carmo et al. (2018) evidenced that monthly adjustments of the stocking rates to achieve target forage offer levels are key to increased animal productivity. Several case studies also demonstrated that stocking rate management at farm scale increased livestock production *via* higher calf weaning weights, pregnancy rates, and increased profitability (Albicette et al., 2017; Do Carmo et al., 2019; Claramunt and Meikle, 2020).

Sward Structure Control

Sward structure is defined as the arrangement of species, plant biomass, and different plant components (leaves, stems, and senescent tissues) in the horizontal and vertical planes (Marriott and Carrère, 1998). Typically, in *Campos* grasslands, several structures coexist, characterized by differences in height, species, and green:dead and lamina:stem ratios. Herbivores interact with such spatiotemporal heterogeneity producing uneven grazing distribution (Parsons and Dumont, 2003), which further creates and maintains heterogeneity and results in variable grazing efficiencies (Ganskopp and Bohnert, 2009), with consequent effects on grassland productivity and biodiversity (Bailey and Provenza, 2008).

Sward structure can impair the production of grazing animals more than forage quality (Azambuja et al., 2020), so grazing intensity should be used also to create optimal sward structures to make the foraging process more efficient (Carvalho, 2013). Thus, sward structure manipulations, such as mechanical mowing or tactical grazing at high stocking rates, are tools that could be used to increase effectively grazed area (Neves et al., 2009) or volumetric density of green leaves in a range of height that it is not limiting for forage intake (Gonçalves et al., 2009). The effect of the manipulation of sward structure was evidenced in calf-rearing experiments in the south of Brazil, which showed that an increase of spring grazing intensity increased livestock productivity in the following seasons (Soares et al., 2005) and in Uruguay which evidenced that maintaining sward height between 6 and 12 cm lead to sustained high levels of livestock productivity over 10 years (Rodríguez Palma and Rodríguez, 2017a).

Forage Stockpiling

Stockpiling forage, defined as forage allowed to accumulate for grazing at a later time (Allen et al., 2011), is a strategy to make "*in situ*" forage banks for use it later in periods of low seasonal pasture growth (Derner and Augustine, 2016) or to mitigate drought effects (Scasta et al., 2016). In most springs and in rainy summers, native grasslands produce a greater amount of forage than grazing animal demand, while during most winters and dry summers, the opposite situation occurs, because primary productivity is highly dependent of precipitations during the end of spring and summer (Berretta et al., 2000). Often, this asynchrony between supply and demand of nutrients occur in all paddocks of a farm, since different paddocks usually grow in sync with weather conditions, and with few adjustments of stocking, resulting in an inefficient use of the forage. The accumulation of forage in small areas, as opposed to dispersed over the whole farm, could avoid energy losses in the grazing process and allow the application of differential nutritional management practices at each paddock.

Stockpiling of forage is a low-cost and easy-to-use intensification option to improve the space-time management of forage in livestock farm systems. However, there is a trade-off between the quantity and quality of stockpiled forage that can be managed by adjusting the duration of the resting period so that stockpiled forage can meet demands of specific animal categories (Mufarrege et al., 1977). Specifically, the area to be stockpiled depends on how the livestock number is in relation to carrying capacity, on the potential growth of the forage in the grazing exclusion period (Fedrigo, 2011), and on the required forage quality and on how much the forage deficit would be in the later shortage period.

Nutritional Management of Livestock

In extensive livestock systems, there are mainly three low-cost nutritional management tools that can be used to improve profitability and reduce the economic risk: (i) matching the breeding period and hence beef cattle and sheep energy requirements with the seasonal pattern of pasture production (Do Carmo et al., 2016), to optimize feeding resources; (ii) prioritizing the feeding of primiparous cows and ewes using high-quality forage resources in order to ensure the functions of growth and reproduction (Spitzer et al., 1995); and (iii) applying short-term (10–14 days) calf suckling restrictions with nose plates (otherwise known as temporary weaning) to reduce energy demand and in consequence increasing the reproductive performance in cows calving in a lower body condition score (Quintans et al., 2009).

These management tools could help us to ensure adequate levels of body condition score at calving, and therefore higher annual pregnancy rates (Quintans et al., 2010, Soca et al., 2013; Do Carmo et al., 2018), and to increase calf weight when suckling restriction is combined with a high forage offer (Claramunt and Meikle, 2020). Most of these tools were developed from the conceptual model proposed by Soca and Orcasberro (1992) that combine indicators of pasture structure and the energy balance of grazing cows to guide the management decisions in *Campos* ecosystems. Aside from that, the preferential allocation of the most demanding categories in better pastures (higher green leaves mass) is another strategy that may help to improve animal performance. Lastly, cattle crossbreds can increase animal production, Do Carmo et al. (2018) evidenced that the control of grazing intensity by manipulating herbage allowances combined with the use of F1 crosses (Hereford × Angus) increased livestock production and the efficiency of energy use.

Input-Based Technologies

Fertilization of Native Grasslands

Forage yield and quality of *Campos* native grasslands is strongly and frequently limited by soil fertility. Fertilizing with N increases primary production, and, at the same time, improves the forage nutritional value (Boggiano, 2000; Jaurena et al., 2014). Two-fold increases in forage production are often found (Boggiano, 2000; Jaurena et al., 2014). A synergistic response between nitrogen and phosphorus addition is reported in Jaurena et al. (2014). These technologies have a particular use to short-term improvements of both forage productivity and quality and could improve animal production from 60 to 200% compared with unfertilized grasslands (Rodríguez Palma and Rodríguez, 2017b). Santos et al. (2008) reported that 200 kg N ha^{-1} year^{-1} increased liveweight gain to 700 kg liveweight ha^{-1} year^{-1}, but soil correction with lower lime and NPK fertilizer (500 kg ha^{-1} 5-20-20) was superior in financial returns. However, fertilization should be used with caution, since it has been found that it could lead to a decrease in species richness (Bobbink et al., 2010) and favors the invasions by exotic species (Shen et al., 2011).

Overseeding of C3 Species Into Native Grassland

Another option to overcome the limitations of native grasslands is overseeding legumes, mainly *Lotus* sp. and *Trifolium* sp., combined with P fertilization (Del Pino et al., 2016; Jaurena et al., 2016), or overseeding annual grasses, mainly *Lolium multiflorum*, combined with N fertilization (Ferreira et al., 2011a; Brambilla et al., 2012), or a mix of legumes and grasses and N and P fertilizers (Oliveira et al., 2015). These technologies are effective strategies to establish productive, high-quality C3 forage species into native grasslands that could be used to reduce seasonality and increase animal performance and stocking rates. However, this technology should be managed with care since it could lead to reductions in plant species richness and facilitate the invasions by exotic species (Jaurena et al., 2016).

Replacement of Native Grasslands by Annual or Perennial Pastures

Sown pastures are made by replacing the native vegetation by annuals or perennials exotic species coupled with high levels of fertilizers. The use of sown pastures is greater in more intensive livestock systems. Sown pastures typically include annual or perennial exotic grasses and legumes coupled with high levels of fertilizers. Most of the annual pastures are winter season (mainly *Avena* and *Lolium*), while perennial pastures are mixtures of grasses (mainly *Festuca* sp. and *Dactylis* sp.) and legumes (mainly *Lotus* sp. and *Trifolium* sp.). Perennial pastures are used to prioritize the feeding of the most demanding livestock categories due to their higher productivity and nutritive value, which could allow for at least a 3-fold increase in animal production (Berretta et al., 2000). However, this superiority is limited by their short persistence, and sown pastures require higher maintenance expenses compared with native grasslands. Notwithstanding the evidence of the short-term increase in productivity, the transformation of native grasslands to crop land changes the original pools and fluxes of carbon (C), nitrogen (N), and phosphorus (P) of that ecosystems (McLauchlan, 2006) in addition to the above-mentioned increased production variability and economic risks.

Pasture Irrigation

Campos grasslands are exposed to high variability in rainfall causing large fluctuations in forage production and nutritional value, which is expected to increase in most future climate change scenarios (Giménez et al., 2009). In this context, supplemental irrigation of native grasslands (Jaurena et al., 2014) or sown pastures may be a strategic tool to ensure a feed basis for the animals. Although the development of this technology in *Campos* grasslands is limited by high initial investments and high running costs, it could be applied in a small area of the farm.

Supplementation

The energy and crude protein contents of native *Campos* grasslands are not enough to meet the potential requirements for growth of young animals during several months of the year (Ramos et al., 2019). Exceptions can be observed in spring or in good soils without water restriction and good management of forage on offer as related by Ferreira et al. (2011b). Therefore, several alternatives of supplementary food have been used to overcome these restrictions using mineral-, protein-, or energy-concentrated supplements, balanced rations, or preserved forage. The supplements could be strategically used to: (i) avoid weight loss during winter, which also has a positive effect on the rest of the productive life of the animals; (ii) maintain forage offer and stocking rate despite low pasture production; (iii) recover primiparous cows or mature cows with low body condition score; and (iv) anticipate slaughter age of fattening animals. However, if supplementation is used to increase the stocking rate at low forage offers, it could lead to overgrazing.

System Technologies

Stocking Methods

For the purposes of this paper, grazing systems are understood as the integrated strategies to manage soil, plant, and animals with the aim to achieve specific social, environmental, and economic results (Allen et al., 2011). Stocking method could be either continuous or rotational. Fenced multipaddock grazing systems allow direct control of the resting period (Allen et al., 2011; Di Virgilio et al., 2019), while in continuous stocking, the control is indirect, *via* stocking rate adjustment. Where paddocks are continuously occupied, grazing animals have more freedom to choose their diet than in the rotational stocking. In smaller paddocks, rotational stocking is used to ensure a higher harvesting efficiency of the forage. Studies carried out in the region have not found evidence of advantages of any stocking method, given the appropriate forage on offer is maintained (Berretta et al., 2000; Jochims et al., 2013). It is worth noting that none of the studies was carried out at the long term or at the farm level.

In *Campos* grasslands, continuous stocking is the most widespread stocking method. Often, this is associated with poor basic infrastructure resulting in farms with a few large paddocks and many small ones (typically nearby the house) and few watering and shade points. Such designs, not based on the pattern of plant communities, animal species, categories, and stocking rates, severely limits the implementation of processes technologies that aim to offer to the animals an optimal sward structure (Carvalho, 2013) that favors the foraging process independently of the stocking method (Carvalho et al., 2019). To put it into practice, it is needed to monitor the forage mass, forage growth, and animal weights and/or monitor forage structure (e.g., pasture height, tussock frequency, etc.). The frequency of monitoring needs to be tailored to the speed at which decisions are taken at farm level.

Silvopastoral Systems

Silvopastoral systems combine trees, grasslands, and livestock under a comprehensive management system. It has been proposed as an alternative model for increasing the sustainability of livestock farms. Trees are not exactly abundant in *Campos* ecosystems, except for the riverbanks and small woodlots of cultivated trees that provide shade and shelter for livestock (Cubbage et al., 2012). Silvopastoral systems play a fundamental role in animal welfare by reducing the caloric stress (Lopes et al., 2016) and also helps to diversify farmers' income. Interestingly, some field plot experiments have demonstrated synergies between pasture, animals, and trees (Fedrigo et al., 2018). However, silvopastoral systems explicitly designed to exploit the synergies between grasslands and forests have not been developed yet in the *Campos* mainly due to the high initial costs for installing trees.

Integrated Crop-Livestock Systems

The rotation of annual crops (2–3 years) alternated with sown grass-legume pastures (3–4 years) is a technology already developed in the Campos ecosystem (Lunardi et al., 2008; Ernst et al., 2018; Alves et al., 2019). These integrated crop-livestock systems (ICLS) were highlighted by Lemaire et al. (2014) as a way to: (i) facilitate the installation of sown pastures and improve the quality of grasslands through regular renovations; (ii) reverse soil degradation and decrease environmental impacts by including multiyear pastures in pure annual crop rotations; (iii) allow a higher diversification of the landscape that facilitate habitat diversity; and (iv) promote a higher flexibility of the whole system to cope with climate and economic hazards. This

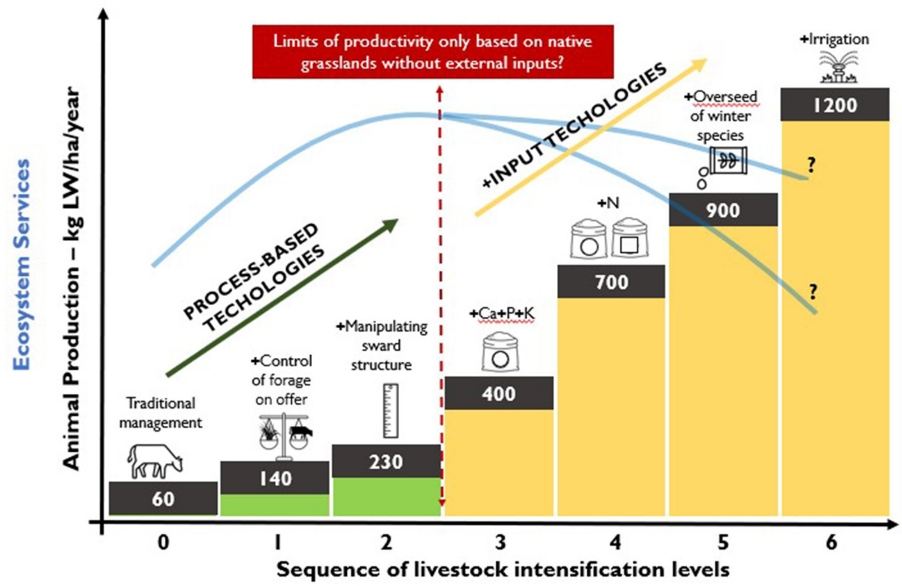

FIGURE 2 | Sequence of livestock intensification across process-based and input technology pathways. The model assumes the increasing levels of potential productivity of a rearing to finishing steers system based on native grasslands of the Pampa biome (Brazilian part of *Campos*) and consequences to the provision of ecosystem services. Adapted from Carvalho et al. (2011) and Nabinger and Jacques (2019), with means from the study area. Nowadays, ecosystem services response curves to livestock intensification are not well-studied, so the decline of the curve may be more or less pronounced depending on the predominance of trade-offs or synergies at the system level.

is a technology partially adopted in livestock farms, especially in those close to agricultural areas. If planned at the territorial level, ICLS can help to improve the profitability of livestock systems and indeed the conservation of *Campos* ecosystems by indirectly valuing the calves, which are highly demanded in regions where ICLS are implemented (De Moraes et al., 2019). In addition, ICLS can buffer native grassland seasonality, so it seems reasonable to recouple crop- and livestock-specialized farms to exploit synergies at landscape level (Garrett et al., 2020).

Evolution of Intensification Approaches in *Campos* Ecosystem

National Programs for Technical Change

In *Campos* ecosystems, the first proposals for technical change in livestock systems based on native grasslands were raised in the 1960s and 1970s. The "New Zealand package" in Uruguay (Alonso and Pérez Arrarte, 1980); "Plan Balcarce" in Argentina (De Obschatko and De Janvry, 1972), and "PRONAP" (Pasture National Program), "PRONEP" (Beef Cattle National Program), and CONDEPE (National Council for Livestock Development) in Brazil (Pinazza and Alimandro, 2000; Bini, 2009) were institutionally subsidized programs that stimulated the replacement of native grasslands by intensively fertilized sown pastures (grasses and legumes) to increase forage production and quality.

These plans were widely incorporated in the most intensive crop and dairy farms. However, they did not have the expected results in extensive systems mainly due to an increase in uncertainty related to the lack of persistence of perennial pastures under local conditions (Alonso and Pérez Arrarte, 1980). Perennial pastures have short longevity in the *Campos* ecosystem (currently 3–5 years), which implied both higher production variability and economic risks (Alonso and Pérez Arrarte, 1980). The question that arises is why sown pastures became successful in dairy farms and why not in extensive livestock systems. One possible explanation is that the dairy industry provides credits to dairy farmers to make cultivated pastures that have a short-term economic return and are profitable, while in livestock extensive systems, this integration does not exist, and cultivated pastures are generally not profitable.

Intensification Levels

In the early 2000s, the existing experimental knowledge concerning the potential of livestock production on native grassland was categorized into six levels of increasing intensification (**Figure 2**). Level 0 corresponds to "typical" or "average" of rearing and finishing systems of beef cattle in the region (Carvalho et al., 2006; Nabinger, 2006). On this basis, controlled grazing intensity (level 1) is a fundamental tool for improving livestock production due to improvements in forage budgets (offer vs. demand) (Maraschin et al., 1997; Do Carmo et al., 2019) which can be improved in a further step (level 2) by the manipulation of sward structure to maintain forage quality and optimize grazing time and maximize forage intake (Soares et al., 2005; Da Trindade et al., 2016). Management using moderate grazing intensity in levels 1 and 2 is pivotal to

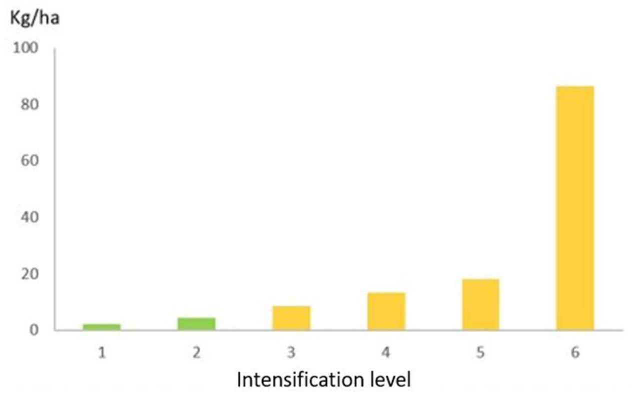

FIGURE 3 | Minimum increase in livestock productivity of a rearing to finishing steer system needed to cover the increased annual costs when 10% of the farm is intensified with each intensification level.

improve primary and secondary productivity (Carvalho et al., 2011). These two low-cost tools for managing native grasslands can provide the "win-win benefits." On the one hand, they increase livestock productivity and reduce system vulnerability. On the other hand, they improve environmental services by maintaining biodiversity and, decreasing beef cattle methane yield and intensity (Cezimbra, 2015) and nitrous oxide emission factor from urine (Chirinda et al., 2019).

Subsequent steps to further increase productivity are based on the addition of external inputs, such as calcium (Ca), phosphorus (P), and potassium (K) (level 3) and N (level 4) to overcome the nutritional limitations of native forage species (Boggiano, 2000). Additional intensification levels can be achieved by combining the addition of fertilizers with overseeded exotic legumes and/or grasses (level 5) (Santos et al., 2008; Brambilla et al., 2012). Lastly, at the highest level of intensification (level 6), native grasslands that are fertilized, overseeded, and irrigated can potentially embody all the previous improvements.

As we move from levels 3 to 6 of intensification, some trade-off may exist between increasing livestock productivity and loss of diversity (Carvalho et al., 2011), reducing the extent of ecosystem services. The minimum level of productivity needed to cover the costs of each level of intensification is low with process technologies, but it increases substantially with each subsequent level of intensification based on the use of inputs (**Figure 3**). This is because each additional step of intensification with inputs increases the financial costs (Santos et al., 2008) and thus the economic vulnerability of the systems. At the same time, these high-productive systems often become more vulnerable to climate variability.

A New Paradigm for Sustainable Intensification at the Farm System Level

The levels of intensification were the first agroecological path that integrates the ecological dimension with farmers' livelihoods in *Campos* ecosystems. The conceptual relationships shown in **Figure 2** indicate the trade-off responses between intensification and ecosystem services. In the first instance, both productivity and ecosystem services could be enhanced by the use of grassland management technologies leading to a win-win situation. However, this form of intensification has a limit imposed by rainfall and the soil nutrient content that determines the amount of forage growth and nutritional value.

To overcome these limitations, input technologies could be used to continue increasing livestock production, but at the cost of reducing many of the ecosystem services, leading to a conflicting situation. Nevertheless, farm system management is challenging, because of the multiple synergies and tradeoffs involved in farmer decisions and by the dynamic non-linear responses of the vegetation. In order to address these complexities, a new paradigm is needed to comprehensively focus on the intensification process at the farm system level. This leads us to propose a new approach shifting from steady-state management tools to integrated strategies that may reduce system vulnerability while ensuring ecosystem service provision.

DISCUSSION

Intensification to Cope With Vulnerability Challenges

In the *Campos* ecosystem, the animals graze outdoors in species-rich grasslands all year round, making the livestock systems highly dependent on the climate and on the prices of products. In consequence, in meat-exporting countries, like Argentina, Brazil, and Uruguay, where subsidies are minimal or inexistent and the prices of the products constantly change, technological development should be oriented toward minimizing the economic risk and the reduction of climate vulnerability. With these conditions, the approach of short-term maximization of livestock production through the massive use of inputs can decouple this finely tuned agroecosystem. The failure of the "New Zealand," "Balcarce," "PRONAP" and "PRONEP," and "CONDEPE" plans in *Campos* ecosystem due to its lack of adaptation to the local extensive livestock systems is a clear evidence of this decoupling process.

As evidenced in **Figure 4**, the substitution of native by sown pastures further increases the already high variability in forage production, increasing the uncertainty of sown pasture production from the third year, as well as both productive and financial risk. For these reasons, we consider that the use of sown pastures, stocking methods, fertilization, and feed supplementation in addition to other intensification technologies can be used strategically to aid and complement native grassland management in the *Campos* ecosystem but not as an ends in themselves. New models for livestock sustainable intensification should optimize the use of a diversity of alternative strategies to increase the quantity of low-cost products while minimizing all possible negative effects on ecosystem services.

Win-Win Intensification Solutions

The challenge of sustainable intensification of livestock production in *Campos* ecosystems is to increase the production

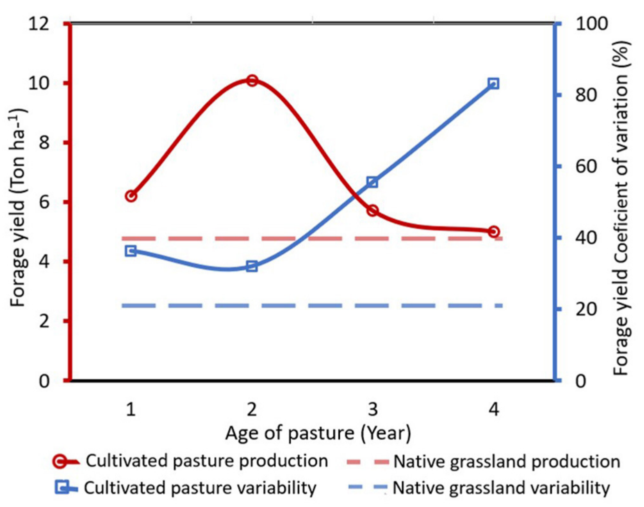

FIGURE 4 | Temporal dynamics of forage yield of sown pastures (solid red line) and its interannual coefficient of variation (solid blue line) compared with native grasslands (dashed lines). Average of mean annual and its coefficient of variation of: (i) the first 3 years of *Festuca arundinacea*, *Trifolium repens*, and *Lotus corniculatus* monospecific pastures from 27 years (1993–2019) of INASE-INIA cultivar evaluations in the southwest of Uruguay and the fourth year from Carámbula (1991); and (ii) native grassland data series of forage production > 10 years in north of Uruguay (Berretta et al., 2001; Rodríguez Palma and Rodríguez, 2017b), east of Uruguay (Bermúdez and Ayala, 2005), and central-eastern Argentina (Bendersky et al., 2017).

and utilization of forage, and its efficiency of conversion to animal products with economic, social, and environmental benefits. Within a context of accelerated intensification, there is a need to adapt to rapid changes and decrease overall vulnerability promoting synergies and reducing trade-offs at the farm system level. For its purpose, the use of techniques to ground the spatial and temporal management of forage and the exploitation of the complementarities among livestock nutrition, nutrient-diverse forage species, and grassland management are key to promoting livestock production under a range of scenarios.

To carry it out, we need to redesign the systems, if necessary, and generate a decision support system to aid farmers' management activities in a complex environment. Therefore, before adding inputs into the system, you must optimize the management so that the fertilizers, species supplement, or system technologies could create win-win situations. Particularly, there is a set of specific low-cost validated techniques that could have a great impact on the productivity and stability of livestock systems in the *Campos* ecosystem. Here, we highlight seven suggested alternative strategies, based on experimental evidence and case studies that incorporate flexibility to deal with uncertainty and help manage system complexity, ultimately boosting resilience:

(i) During spring, when pasture growth is regularly high, the generation of modules of *in situ* stockpiling (deferred paddocks) can be used to: (a) optimize forage structure and therefore high-quality forage harvest in the non-deferred paddocks by adjusting the stocking rate to the period of luxurious forage growth; (b) *in situ* forage stockpiling to face climate uncertainty and to compensate for the increased variability in pasture production generated in areas intensified by input technologies; and (c) favor seedling recruitment and seed production of the most palatable species and enhancing the recovery of the most overgrazed areas. To adopt this alternative management, farmers need to exclude at least one paddock, something easily achieved by those already using alternate or rotational stocking in their grazing management systems.

(ii) During summer, when pasture growth shows high variability, the use of: (a) calf suckling restrictions with nose plates (temporary weaning), or early weaning for cows with a body condition score below the target, are fundamental to achieving a high reproductive efficiency through a better management of the nutritional supply/demand ratio; (b) stockpiled forage and/or feed supplements in cows and sheep could maintain the forage on offer, if necessary; and (c) creep-grazing to the calves while restricting cow access in small specially designed areas of sown pastures or fertilized native grasslands could provide high-quality forage.

(iii) During autumn, when pasture growth begins to decline, the: (a) annual stocking rate adjustment, through selling cull cows and less productive animals and/or by the early weaning of calves, is central to recover the body condition score of the groups of target cows and to avoid overgrazing in native grasslands; and (b) the generation of modules of paddocks for stockpile legume overseeded or nitrogen fertilized grasslands to offer this forage to the most demanding livestock categories in the following winter.

(iv) During winter, when pasture growth is the lowest, the use of: (a) low-quality forage accumulated in the stockpiled modules could be offered to the less demanding animal categories through restricted time access combined with protein supplements to sustain the forage on offer on the native grasslands, and therefore decreasing overall overgrazing; (b) high-quality forage produced in farm modules of sown pastures specially designed to overcome native grassland seasonality and to be offered to the most demanding livestock categories (e.g., legume overseeded, sown or fertilized pastures preferably assigned to calves, heifers, or primiparous cows), could have a positive impact on the rest of the productive life of the animals.

(v) During below-average rainfall seasons, the use of: (a) stockpiled forage and/or supplemental feed could be used to sustain forage on offer despite low pasture growth, reducing overgrazing in native grasslands; (b) efficient irrigation to pastures with high potential growth rate could be used in small areas to overcome the forage deficit.

(vi) The implementation of modules of specialized rotational stocking by splitting paddocks with uniform plant communities, and at the same time with available water and shade could be used to improve pasture management. In these conditions, the resting time of paddocks can be directly controlled according to the thermal sum required for leaf expansion of desired species or functional types, and specific management targets, as well as post-grazing forage height. Again, what is important is to offer to the animals an optimal sward structure (Carvalho, 2013) to optimize the utilization and growth of both native and sown pastures, which is facilitated by using multiple-fenced paddocks.

(vii) Diversify farm system income using silvopastoral or crop-livestock systems, and at the same time, exploit its advantages to improve animal welfare and perennial pasture renovation, respectively.

Native Grasslands at the Core: A New Paradigm for *Campos* Grassland Intensification

Based on the results of the previous models suggested for livestock intensification in Campos ecosystem, we propose to further develop the existing paradigm including resilience-based concepts underlined by Bestelmeyer and Briske (2012) and scaling it from paddocks to farming systems. Sustainable intensification aims to increase grassland productivity while increasing sustainability (Garnett et al., 2013). To overcome this challenge, the abovementioned management, input, and design intensification strategies will help to increase the ability of livestock farming systems to cope with external shocks (climate uncertainty and/or prices volatility). Thus, the question that arises is how to use these strategies to solve problems in different farming systems and dynamic conditions.

At the farming system level, native grassland is central to assuring the main source of ecosystem services, so process-based and input-based technologies orbit native grasslands to build a farming system which is predominantly based on native grasslands. Livestock intensification options are spatiotemporally designed to cope with native grassland vulnerabilities. Which levels of livestock intensification and how and when they will be arranged depend on a co-designing process with local stakeholders. To overcome these challenges, we propose a new model for livestock sustainable intensification that highlights the role of the optimal management of native grasslands as a cornerstone to increase productivity and preserve sustainability. This proposal is focused on small and medium livestock farmers that have access to public extension programs and will be called "native grasslands at the core" (**Figure 5**).

Given that the best environmental functioning is achieved through well-managed native grasslands (Nabinger et al., 2011; Modernel et al., 2018), we proposed that livestock intensification strategies should focus on optimizing the management of the native grasslands base (the core). One way to achieve the optimal management of native grasslands is to create specialized modules within livestock farms to fulfill a specific function that may help to improve the overall farm productivity and resilience. Examples of these modules are shown in **Table 1**.

In this context, adaptive management, a structured approach that uses monitoring to make simple decisions in complex systems that are exposed to changing conditions (Briske et al., 2017), could be used to guide can aid farmers' decision-making process. Adaptive grazing management strategies are a set of envisaged alternatives to be selected with the assistance of specialists in order to attenuate the main vulnerabilities of an agroecosystem, and to react to specific events that may affect them. In this paper, we propose an intensification framework for extensive livestock production systems that focuses on the role of the optimal management of native *Campos* grasslands. In this framework, short- and medium-term stocking rate adjustment and sward structure control are key to increase productivity and resilience.

We envisage a co-innovation approach as described by Albicette et al. (2017) with the participation of researchers and extension agents to aid farmers in selecting, monitoring, and evaluating the intensification options. This methodology could be strengthened by the development of state-and-transition models as systematic strategies for improving native grassland management by a structured decision-support process. These models could be implemented in an approach similar to that proposed by Bestelmeyer et al. (2017) but with an increased emphasis on the integration of multiple options to intensify management while protecting the native grassland core. For these to be achievable in commercial farms, a portfolio of complementary tools is available, such as forage stockpiling, livestock supplementation, sown pastures, conserved forage, legume-, or grass-overseeded native grasslands, and nitrogen and phosphorus fertilization: To avoid extensive native grasslands replacement or degradation, these options should be restricted to specially designed modules.

Finally, the design of the agroecosystem should be readapted as needed through: (i) using grazing management strategies adjusted to the available plant communities and local infrastructure; (ii) creating new intensified modules to improve the functions that most limit the sustainability of the system; and (iii) include other synergic agricultural activities like silvopastoral or crop-livestock systems. In **Figure 6**, a schematic of an adaptive management plan depicts the use of options to actively prepare for a drought, and then to react to it.

The economic results and the risk of implementing the proposed system of intensification should be assessed at the system level and compared with other intensification options. To this purpose, some economic indicators like profitability, gross margin per hectare, financial dependence, time lags between investment and benefits, and feed autonomy should be calculated. Additionally, risk perception is a key factor in the adoption of a new technology in agriculture (Marra et al., 2003). Because whole-system risk reflects the cumulative effects of the climate, price, political, and human factors influencing the farm profit, it needs to be assessed dynamically in each specific context to aid the decision of alternative intensification options.

So far, we have considered that the synergies of land use change within an intensified based system should at least offset environmental costs. However, in order to achieve sustainable intensification at the landscape or regional level, it is also important to consider the society's priorities. At this scale, it is necessary to calculate the public costs of the loss of native grasslands ecosystem services, such as soil preservation, water provision, and landscape scenic beauty. Therefore, a proposal of sustainable intensification should also consider the public costs of native grassland ecosystem land use change, e.g., by the increased costs for the provision of drinking water to the

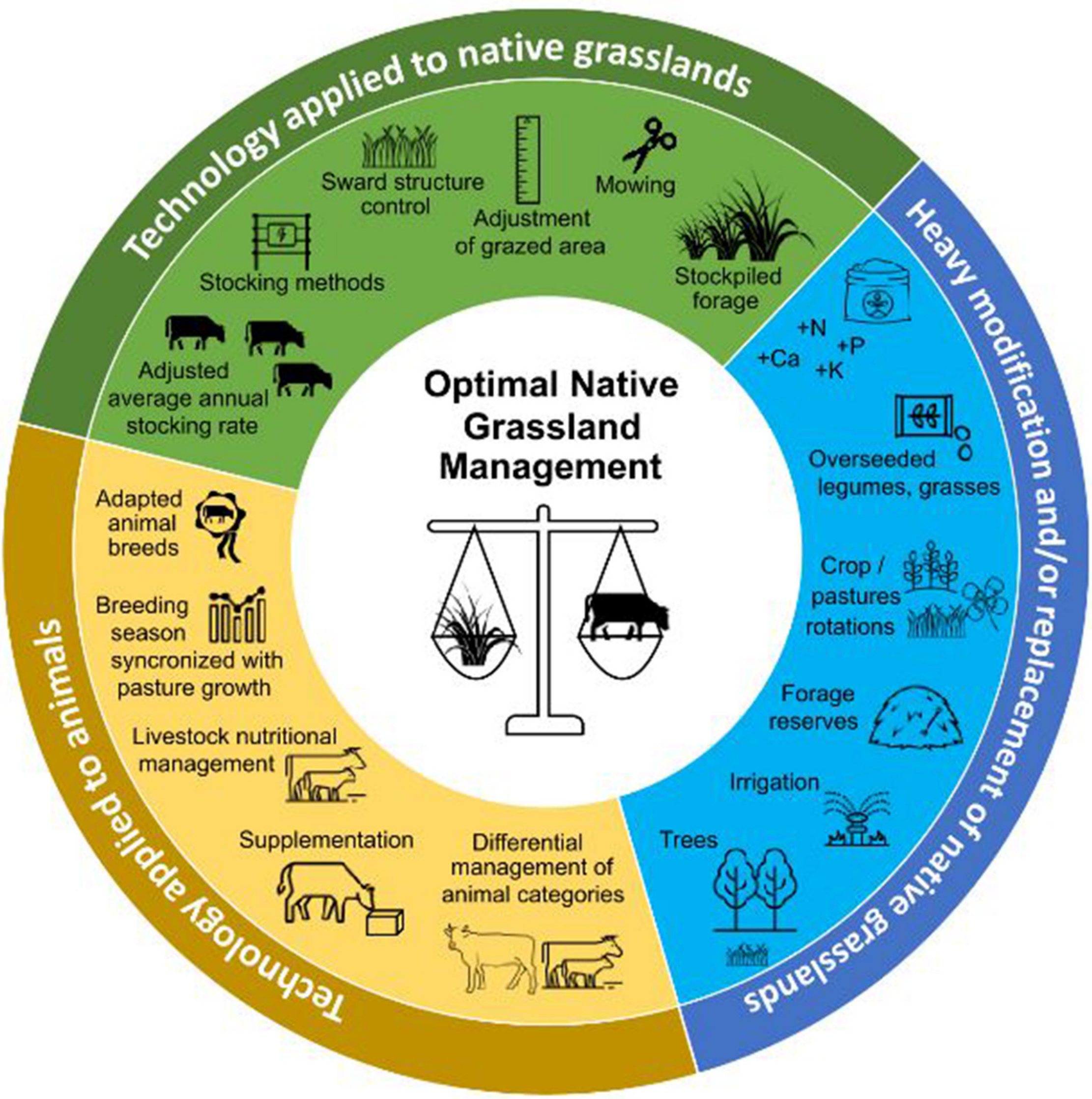

FIGURE 5 | A new model for livestock sustainable intensification that describes the role of technology applied to livestock management (orange), to modified or replaced native grasslands (blue), and to native grasslands (green) to achieve optimal native grassland management.

population after land use change. At national levels, institutions and government policies could promote the proposed model of intensification by defining regulations and incentives that facilitate the capacities of managers to make decisions regarding the productive conservation of their socioecosystems.

Summarizing, in the proposed framework, we consider that the dilemma is no longer whether or not to use input technologies and becomes how to combine the use of input technologies to boost the core. For example, sown pastures could play a key role to reduce forage production variability over the year, to improve the forage growth, quality, and animals' intake of native grassland forage, or to improve the nutrition of the most demandant animal categories among others. To this end, we propose to construct multidimensional adaptive strategies that would intensify the capacity of livestock systems to cope with ecosystem, climate, and market changes, rather than simply reacting to current conditions. The intensification proposed in this paper is proportional to the management intensity and not to the amount of external inputs applied. However, increasing management intensity requires: (i) more knowledge of how grassland vegetation responds to management practices such as grassland intensity, deferment, or fertilization; and (ii) more time dedicated to monitoring the condition of the pastures and animals and for decision making over time. Our expectations are that this new integrated management scheme is an adaptive approach that can be used to make better decisions to cope with future challenges and to make livestock production systems in *Campos* ecosystems

TABLE 1 | Specialized modules within livestock farms to carry out a function that helps improve productivity and resilience of the whole system.

System objectives	Management strategies	Synergies	Trade-offs
Improve forage quality to comply with most demanding categories	Modules of sown pastures	Complement native grasslands production and avoid overgrazing	Reduced diversity
Improve gorage utilization efficiency by controlling resting period and post-grazing pasture height	Modules of rotational stocking	Optimize forage structure, growth, and use	Increased costs and knowledge to manage
Improve intake and diet quality by controlling grazing intensity and forage structure	Modules of continuous stocking	Optimize forage structure, growth, and use	Increased knowledge to manage
Forage stocks as a climate insurance	Modules of "stockpiled forage."	Reduce vulnerability and restore overgrazed areas	Reduced forage quality
Reduce climatic effects on livestock and diversify production	Modules of silvopasture or small woodlots	Improve animal welfare and diversify the income	Reduced forage productivity
Reduce climatic effects on livestock and diversify production	Modules of crop-pasture rotations	Complement native grasslands production and diversify the income	Reduced diversity

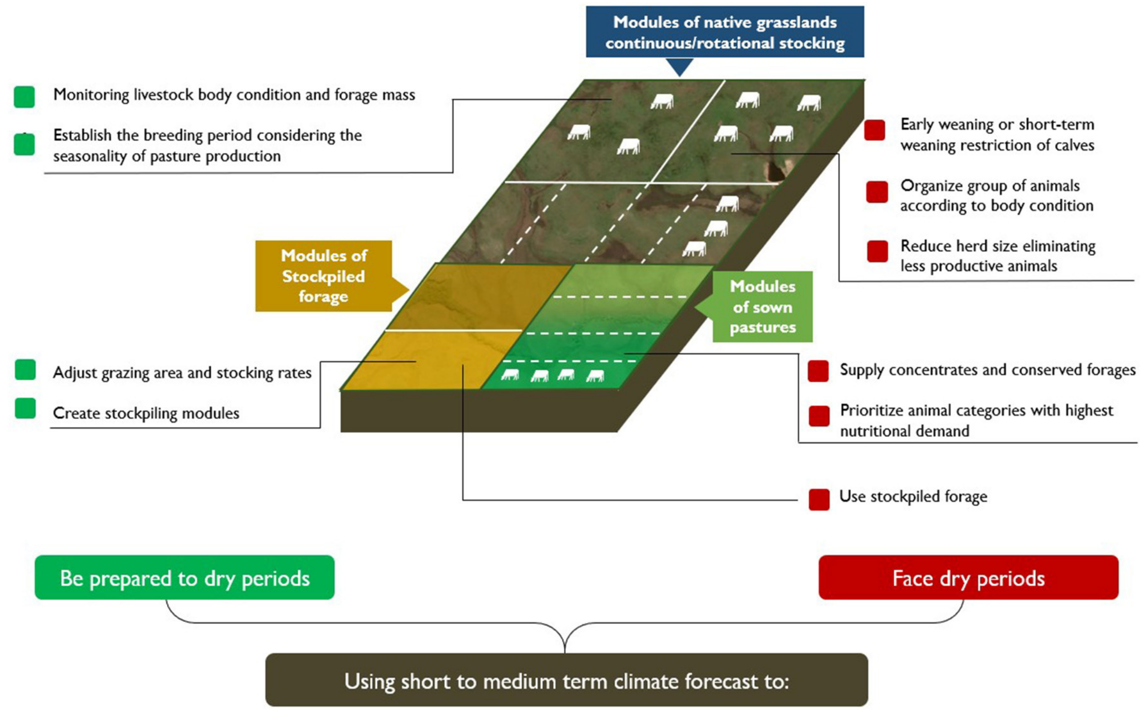

FIGURE 6 | An example of an adaptive management plan with proactive (drought anticipation) and reactive (drought response) adaptation practices suggested to cope with drought in *Campos* livestock farm systems.

more sustainable, despite the need for intensification and greater profitability.

FUTURE ISSUES

Particularly, whole-farm design models are needed to quantitatively analyze the impacts of a specific combination of tools and strategies at the farm system level. This will allow to select the best alternative models of intensification to generate new knowledge and to enhance innovation processes at farm system scale. For that purpose, farmlet experiments are a valuable tool for testing ecosystem service response to alternative farm system models of livestock intensification. The generated knowledge could be used to meet future market demand for food safety, animal well-being, and product quality, as well as to certify the state of relevant environmental variables such as carbon and water balances. Lastly, more research is needed on how to proceed with the transition between traditional and sustainable intensified livestock systems in the *Campos* ecosystem.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available for because data is private. Requests to access the datasets should be directed to Martín Jaurena, mjaurena@inia.org.uy.

AUTHOR CONTRIBUTIONS

FL and MJ conceived the topic and the initial approach. MJ analyzed and interpreted the information and wrote the first draft of the manuscript. MD, TD, JS, DB, FM, MP, PS, PC, FQ, RP, CN, and FL contributed with local information and critically discussed the new paradigm. FM designed the figures. MJ, TD, CN, MD, FL, and PC rewrote it. All authors contributed to the article and approved the submitted version.

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REVIEW
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Vegetation Options for Increasing Resilience in Pastoral Hill Country

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Steep, uncultivable hill country below 1,000 m comprises about 40% of New Zealand's land surface area. Hill country farmers require options to increase the resilience of their farms to climatic and economic extremes while addressing soil conservation and water quality issues. We profile and discuss two options that can assist in transforming hill country. The first comprises a simple approach to grazing management in hill country pastures to increase pasture resilience and the second approach focuses on including selected forage shrubs (and trees) to create grazed pasture-shrublands. Deferred grazing, the cessation of grazing from flowering until seed dispersal of the desirable species in a pasture, is an old practice which has novel applications to improve resilience of hill country farming systems. We draw on current research and practitioner experience to demonstrate the impact of deferred grazing on the resilience of the deferred pasture and the farm system. We propose that deferred grazing will: (i) increase resilience of a pasture by enabling it to better recover from biotic and abiotic stresses and (ii) reduce the risk of nutrient and sediment losses in hill country by increasing ground cover, rooting depth and soil structural stability. Introducing woody forage shrubs into hill country pastures is another option that can improve farm profitability and resilience to current and future economic and climatic variabilities. The extensive root networks of shrubs can increase soil structural stability and reduce the risk of soil erosion. In addition, shrubs can supply many other ecosystem services, such as forage and shelter for livestock. In this paper, we discuss: (i) the potential benefits of a grazed pasture-shrubland at farm, landscape and national scales; (ii) candidate woody exotic and indigenous forage species; and (iii) priorities for research.

Keywords: grazing management, woody forages, hill country, pasture management, deferred grazing

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INTRODUCTION

Steep, uncultivable hill country below 1,000 m, which is generally > 20° slope, comprises about 40% of New Zealand's land surface area (Mackay, 2008). In the farmed areas of these landscapes, the livestock grazing systems that dominate rely on perennial pastures because of: (a) an inability to cultivate widely due to moderate to steep slopes; (b) the need to avoid soil disturbance on highly erodible "soft-rock" soils; and (c) the generally mesic Mediterranean-type climates with even rainfall distribution throughout the year (Kriticos, 2012). These systems use year-round animal grazing *in situ*, as this is the most labour- and energy-efficient means of harvesting forage on hills. Pastures are based on grass-clover mixes, in order to combine the high photosynthetic assimilation capacity and grazing tolerance of grass with the nitrogen (N)-fixing capacity of legumes. However, species diversity within these functional groups is high (Dodd et al., 2004), with variable contributions from adventive grasses, clovers and forbs which colonize the edaphic mosaic.

Lolium perenne L. has been the most widely sown pasture species due to its relative ease of management, high productivity given suitable conditions, palatability, and ease of access to commercial cultivars (Lee et al., 2012). In the late 1960s, *L. perenne* was included in all sown mixtures (Lancashire et al., 1979) and by the mid-1970s, *L. perenne* comprised over 70% of the pasture grasses certified in New Zealand (Hunt and Easton, 1989). There remains a strong focus on genetic improvement of *L. perenne* for New Zealand's pastoral sector (Lee et al., 2012), but in hill country *L. perenne* is not the dominant grass. Other perennial species, such as *Agrostis capillaris* L. and *Anthoxanthum odoratum* L., are generally more abundant and better adapted to low fertility soils and close grazing by sheep and cattle. However, these species are of lower feed quality and their seasonal growth pattern is less aligned with animal demand. Other cultivated grass species, such as *Dactylis glomerata* L. and *Festuca arundinacea* Schreb. have received some attention in breeding programs, as they are more drought tolerant than *L. perenne* (Turner et al., 2012) and better suited to future climate scenarios in which drought is more prevalent (Sheffield and Wood, 2008).

In this context, we consider that the most useful way to think about resilience relates to the pressures on these desirable sown species, and whether they are persistent and maintain their persistence and the resultant productivity of high-quality herbage. In terms of the engineering model of resilience (Holling, 1996), such pressures act to reduce the abundance of desirable plant species, and shift pasture community composition toward low cover and domination by less desirable species [e.g., unpalatable plants, short-lived annuals (Sheath et al., 1984)]. Resilience is indicated by the ability of the sown community to recover after stress or disturbance, rather than revert to naturalized species (Dodd et al., 2004). Several pressures are relevant, including climate and weather patterns, prevalence of erodible soils, soil fertility, over-grazing and pest outbreaks (Tozer et al., 2011).

Decades of research on New Zealand hill country productivity has tended to focus on ensuring the productivity of desirable "improved" pasture species, through: (a) soil fertility—i.e., improving soil nutrient status through fertilizer application to enable the persistence of highly productive species of the genera *Lolium* and *Trifolium* (Kemp and Lopez, 2016); (b) grazing management—i.e., how to balance the need to maximize dry matter (DM) intake with the need to maintain growing points and persistence of desirable species (King et al., 2016); and (c) to a lesser extent, increasing the diversity of high feed quality pasture species suited to hill country—i.e., those better adapted to lower soil fertility, variable soil moisture content and poorer grazing control (e.g., Barker et al., 1993). More recent work has attempted to establish high quality forages though aerial herbicide and seed applications as a means of rapidly increasing productivity (Lane et al., 2016), but this carries high costs and risks associated with weed ingress and erosion.

Further productivity gains on sloping land are challenging for several reasons, including: (a) slope- and aspect-induced variation in soil temperature and moisture (Radcliffe, 1982); (b) fertility transfer by grazing animals *in situ* creates microsite variation that is difficult to counter (Hoogendoorn et al., 2011); (c) there are limitations to leaf area index achievable with herbaceous species under grazing, and therefore there is a photosynthetic capacity limit (Parsons et al., 2011); (d) there is limited ability to increase N input (the major limiting nutrient) without negative environmental impacts on water resources (Dodd et al., 2016); and (e) there are limitations to augmenting rainfall via irrigation in hills because of infrastructure costs and risks of nutrient and sediment losses into waterways. Usually reversion from sown species to more diverse mixes of naturalized grasses and forbs occurs, largely because of high spatial variability in the "habitat" for species (localized soil, climate and defoliation regimes). In the absence of grazing animals this reversion continues to woody species (Bergin et al., 1995). Note that in New Zealand, fire is not a major driver of vegetation structure (that might prevent encroachment of woody species).

We need step-changes in forage management to overcome these limitations and focus more on improving the resilience of the herbage resource, and here we discuss two possibilities. The first option—deferred grazing—retains a focus on herbaceous species but changes grazing management to maximize the resilience and productivity of desirable species. Deferred grazing, the cessation of grazing from flowering until seed dispersal of the desirable species in a pasture, is an old practice (e.g., Suckling, 1959) which has novel applications to improve resilience of hill country pasture systems by enabling pastures to better recover from the inevitable biotic and abiotic disturbances (Holling, 1996) and lower their environmental footprint. The second option changes the forage base by integrating woody species, thereby increasing photosynthetic capacity in the vertical plane, and improving resilience to current and future pressures through diversity in functional plant types (Mori et al., 2012).

Our two alternative strategies also offer opportunities to improve the environmental outcomes of farming. Increasing pasture production has compromised other important ecosystem services, such as clean water and native fauna habitat (Van den Belt and Blake, 2014). Public awareness of these issues is increasing (Hughey et al., 2010) and pressure on farming communities to reduce these impacts has focussed on three broad policy and regulatory areas: water quality, biodiversity and greenhouse gas emissions (Anon, 2015, 2016, 2019a). The two approaches introduced here, deferred grazing management and the integration of woody vegetation into hill country pastures, can harness opportunities to provide a much wider range of ecosystem services than providing feed, including, for example, enhanced soil carbon sequestration, increased soil integrity and intactness protecting waterways from runoff of sediments and nutrients, and a more diverse habitat that will support a greater biodiversity contributing to pest control and pollination services of hill country ecosystems.

DEFERRED GRAZING

Ecophysiological Processes

Harnessing the Reproductive Cycle

Pasture management in New Zealand has focused on maximizing the quantity of high quality herbage produced throughout the year to better match feed supply and livestock demand. To achieve this, research has generally focused on maintaining pastures in a green leafy state and preventing *L. perenne* from flowering and producing seed as reproductive tillers rapidly lose nutritive value (e.g., Hodgson, 1990). With an increasingly volatile climate, pest pressures and the population collapse of desirable species, ensuring that pastures are resilient and can maintain high proportions of productive species is of concern to farmers (Daly et al., 1999; Tozer et al., 2014; Dodd et al., 2018). This has led to questioning the current paradigm of pasture management and a search for more resilient and sustainable management strategies that enable a reliable supply of high quality forage despite these pressures.

The ability of a pasture to recover from stresses such as drought is determined by the net effects of tiller birth and tiller death during the seasons and the ability of a plant to replace dying tillers (Colvill and Marshall, 1984; Matthew et al., 2015). Increases in tiller size and leaf area can offset a decline in tiller populations that occurs as herbage mass increases (Matthew et al., 2015). However, tiller population decline can also occur through the impact of stresses; thus in the longer term the number of tillers is an important proxy for persistence, as plants with fewer tillers are more vulnerable to abiotic and biotic stresses (e.g., Korte and Chu, 1983). Therefore, strategies that increase tillering of perennial pasture species are likely to increase resilience.

To increase tiller densities in the longer-term and to improve pasture resilience, we propose that management should be more closely aligned to the reproductive development of these species and that flowering and seed production of desirable species should be allowed to occur in some paddocks in some years. This strategy will result in:

(i) An initial decline in vegetative tiller densities in late spring/summer;
(ii) Prioritization of carbohydrate for developing reproductive stems;
(iii) Accumulation of storage carbohydrate in plant bases over the reproductive period;
(iv) Accumulation of root biomass over the reproductive period;
(v) An enforced dormancy of tiller buds over summer in hot and dry environments;
(vi) Release of tiller buds and a flush of tillering in autumn;
(vii) Seedling recruitment in autumn of desirable species from the seedbank, depending on the length of the rest period and the species being rested;
(viii) An increase in tillering and herbage accumulation following the deferred period.

We further propose that with increasing levels of abiotic and biotic stresses, an increasing period of rest is required, with full reproductive development being required in the most stressful environments, on a proportion of the farm in an annual rotation.

In the following section these ecophysiological processes are discussed in the context of developing more resilient hill country pastures. We have focused on the ecophysiology of *L. perenne*, given the importance of this species in New Zealand farming systems and the extensive body of scientific literature on its ecophysiology. Impacts on legumes are also briefly discussed.

Family Feud for Carbohydrate

Korte (1986) described *L. perenne*-based swards as consisting "of a dynamic population of short-lived tillers of different ages," with the rate of tiller birth varying during the year (Duchini et al., 2018). L'Huillier (1987) documented a flush of tillering in spring and early summer, with the highest rates of tillering occurring between November and January, and low and variable rates occurring between February (end of summer) and October (mid-spring) in northern North Island pastures grazed by dairy cattle.

Vegetative Growth

During vegetative growth, water soluble carbohydrate (WSC) is transported to expanding roots, tillers and leaves at the shoot apex (e.g., Ryle, 1970). A small, but biologically significant, proportion of carbon is incorporated into long-term storage carbohydrate, which is typically stored in stem bases or stolons of grasses and legumes (White, 1973; Danckwerts and Gordon, 1987). Over an extended period, the amount of carbohydrate builds up, typically in the base of the stem, providing considerable reserves to recover from defoliation (Alberda, 1957; White, 1973; Danckwerts and Gordon, 1987).

Daughter tillers compete with parent tillers for WSC, which can lead to reduced tillering in times of stress (Donaghy and Fulkerson, 1998). Defoliating low and continuously into the crown of the plant can deplete WSC reserves and lead to tiller and plant death. In contrast, defoliation coinciding with the 3-leaf stage of *L. perenne* to 5 cm is optimal for the regrowth, productivity and persistence of the *L. perenne* plant (Donaghy and Fulkerson, 1998). Defoliation at the 3-leaf stage also enables WSC to be allocated to root growth and daughter tiller initiation, which occur after stubble WSC reserves are replenished (Donaghy and Fulkerson, 1998).

Reproductive Growth

During mid-spring to early summer, *L. perenne* and *Trifolium repens* L. are particularly vulnerable to environmental stresses due to the plant population re-establishing itself through new tillers (in the case of perennial ryegrass), fragmentation of parent plants and production of new smaller plants [in the case of *Trifolium repens*, and production of seed (Edwards and Chapman, 2011; Macdonald et al., 2011)]. While this reproductive development period is a major focus of crops, it has often been neglected when investigating pasture persistence (Kemp and Culvenor, 1994). Yet this period provides opportunities that can be harnessed to improve pasture resilience as shall be discussed in this paper.

Perennial ryegrass tillers that become reproductive are generally formed before winter (Korte, 1986). Reproductive development and flowering of perennial ryegrass are triggered after a vernalisation period and in response to a change in daylength and temperature (Halligan et al., 1993). When reproductive stems begin to elongate in mid- to late spring, leaf initiation and tiller bud development are suppressed (Jewiss, 1972). During this period, there is a continual feud for carbohydrate between parent and daughter tillers. Small, shaded tillers are unlikely to obtain the resources they need to survive. In contrast, larger tillers are not dependent on other tillers for WSC and being taller, are better positioned to capture light and photosynthesise (Ong et al., 1978; Colvill and Marshall, 1984). Given this feud, few vegetative tillers survive the period of reproductive growth in undefoliated swards.

During reproductive development, WSC is prioritized for inflorescence and seed development, although a small but biologically significant amount of WSC moves downwards from the reproductive tiller. It is stored in the base of the plant and remobilised for seed production and growth of new tillers (Hampton et al., 1987; Matthew et al., 1991).

The new tillers produced after flowering provide the bulk of flowering tillers in the following year, and are critical for the longevity of a ryegrass plant and for persistence (Korte, 1986; Matthew et al., 2015). Tillers produced after flowering are subjected to less competition for carbohydrate (due to the removal of competition with reproductive tillers) and their chance of survival can be much greater.

One of the most dramatic impacts of post-anthesis tillering on tiller generation and survival of *L. perenne* is documented by Waller et al. (1999) in summer-dry south western Victoria, Australia. New daughter tiller buds were produced at the base of reproductive tillers which died after setting seed. These buds remained dormant over summer but new tillers emerged in autumn when soil temperatures were lower and the soil moisture content was adequate for growth. Over 50% of reproductive tillers survived over summer and were present in autumn, while in contrast, only 12% of tillers that were vegetative in late spring survived until the autumn rains, when new tiller production occurred (Waller et al., 1999). This corresponded to a 15-fold greater production of new tillers from reproductive tillers than from vegetative tillers during the autumn (Waller et al., 1999). Tillers produced from reproductive tillers were also 25 times more likely to survive than those produced from vegetative tillers (Waller, 2002). In addition, reproductive tillers were able to produce seed, which culminated in many seedlings in the following autumn (Waller et al., 1999).

Based on a knowledge of tiller birth and death as described above, a range of approaches have been proposed to increase tillering. Their impacts on phenological development, ecophysiology, benefits, risks and constraints are summarized in **Table 1**, **Figure 1** and are discussed henceforth.

Negligible Reproductive Development

Hard grazing in spring to prevent reproductive development can promote tillering (e.g., Brock and Hay, 1993). In situations where soil temperatures, moisture deficits and nutrients are unlikely to be limiting, an intensive grazing regime can reduce shading and accumulation of dead material. In this situation, a large proportion of the leaves contribute to photosynthesis and lead to high rates of assimilate and biomass production. Hard grazing during spring, to maintain the tiller populations, given adequate soil moisture over summer, can therefore be used as a strategy to increase tiller density in the following autumn. However, the increased tiller density with lower herbage biomass may not be sufficient to compensate for the associated loss in leaf area and light capture (Matthew et al., 1996). This can lead to a decline in leaf area index, tiller populations and reduced pasture persistence. The risk is heightened in a dry summer when intensive defoliation can result in mortality of *L. perenne* tillers and plants (Brougham, 1960). Root growth at depth may also be compromised. This may restrict access to soil moisture during drought and compromise recovery after a drought (e.g., Korte and Chu, 1983).

Moderate Reproductive Development

Tiller bud development is inhibited during flowering, but buds are released if the inflorescence is removed (Matthew et al., 1991). Matthew et al. (2015) proposed harnessing the post-anthesis tillering perennation strategy of modern New Zealand *L. perenne* cultivars by decapitating the inflorescence to stimulate tillering (Xia et al., 1990; Garay et al., 1997a,b). Root growth can also be enhanced by allowing moderate reproductive development (Matthew et al., 1986). However, stimulation of daughter tiller production in late spring after decapitation may leave daughter tillers vulnerable to drought stress over summer. *"Provided daughter tillers are formed before drought stress occurs, they may simply delay the development of secondary and tertiary tillers until conditions become favorable for growth*" (Xia et al., 1990). This assumes that flowering is sufficiently late in the season for further tiller development to be delayed over summer and that available soil moisture enables survival of daughter tillers over summer The strategy has been applied successfully from plot to farmlet scale with increases in tillering and dry matter production (e.g., Matthew et al., 2000, 2016; Da Silva et al., 2004). However, from a management perspective, targeting grazing to a narrow range in phenological development can be operationally challenging and the benefits have not always been realized (Bishop-Hurley et al., 1997; Bishop-Hurley, 1999). For example, one attempt to implement late control in a self-contained farm system failed to generate the anticipated differences between treatments in herbage mass, and consequently effects on sward behavior were negligible (Bishop-Hurley et al., 1997).

Full Reproductive Development

A third strategy involves preventing buds at the base of the reproductive stems from forming tillers post-anthesis so that tiller buds enter enforced dormancy with the onset of hot dry summers (Waller and Sale, 2001). Tillering is then delayed until autumn when conditions are conducive for tiller buds to be released and tiller growth to occur (Korte and Chu, 1983). This can be achieved by resting a pasture from grazing in late spring until late summer (deferred grazing). This strategy also enables seedling recruitment to occur, which can assist in population growth of desirable species. "Autumn clean-up hard grazings" are important to reduce the presence of dead and sheath material

TABLE 1 | Grazing management approaches to increase resilience in perennial pastures.

Factors to consider	Grazing approach		
	Rotationally grazed throughout spring and summer	**Moderate reproductive development (rested late spring–early summer)**	**Full reproductive development (rested late spring–late summer)**
Stress mitigation suitability	• Low biotic/abiotic stress	• Moderate stress	• High stress
Phenological development	• Negligible reproductive development	• Desirable species flower	• Desirable species flower, senesce, and shed seed
Plant processes	• Reduced shading leads to maintenance of high tiller density in spring • Low opportunity to accumulate storage carbohydrates • Negligible opportunity to harness post-anthesis tillering • Shallower roots	• Some shading, increased leaf senescence and loss of tillers • Some translocation of carbohydrate to tiller bases • Post-anthesis tillering encouraged from early summer onwards • Moderate root depth	• Severe shading and initial reduction in tiller density • Increased storage of carbohydrates • Post-anthesis tillering encouraged in autumn • Increased tiller density and herbage production following the deferred period • Greater root mass • Litter accumulation
Benefits	• Maintains pasture quality • Maintains tiller densities in the short-term • Enhances growth of large leaved clovers	• Limits negative impact on pasture quality • Can increase tiller density from early summer onwards • Negligible seedling recruitment • Can enhance clover growth and seed production	• Better control of pasture quality over the whole farm • New tillers produced from autumn onwards (avoids soil moisture deficit stress and associated competition over summer) • Extensive seedling recruitment possible • Provision of drought feed and better match of feed supply and demand • Clover growth enhanced through improvements of soil microclimate and manipulation of closing and opening times • Easy to apply, low cost strategy
Risks	• Can lead to a low leaf area index and perennial grass population decline • New tillers vulnerable to stresses and increased mortality over summer • Lower root mass makes plants more vulnerable to drought, pest invertebrates and overgrazing • Negligible seedling recruitment	• Tillers produced post-anthesis vulnerable to drought stresses and increased mortality over summer • Narrow grazing window to target anthesis—can be easily missed	• Weeds could increase if insufficient desirable pasture species • Dead residue not adequately removed at end of deferred period leading to poor subsequent pasture quality in deferred paddocks • Suppression of clover growth depending on closing and opening times and perennial grass tiller density • Inappropriate timing of resting the pasture (i.e., excluding livestock and resuming grazing) could have unintended negative impacts on pasture composition
Constraints	• High stock numbers needed in spring to maintain pasture quality over the whole farm	• Sufficient feed available to drop some paddocks out of rotation • Difficult to apply to multiple paddocks	• Sufficient feed available to drop some paddocks out of rotation • Hard grazing with appropriate stock class required in autumn to allow light penetration to the base of the plants and promote tiller growth

that accumulate over summer. This increases the penetration of light into the base of the sward to promote the development of new tillers and will increase their survival (Hunt and Brougham, 1967).

Thus, deferred grazing can enable a dual pathway for enhancing resilience—through the production of daughter tillers from existing plants given sufficient resources, and through the production of seed and seedling recruitment from the seedbank. The beauty of this insurance policy is that if the environmental conditions are not conducive for *L. perenne* survival over summer, the population can be maintained through seedling recruitment, as occurs in pasture renewal.

Impacts of Deferred Grazing

Sward Characteristics

Our understanding of the ecophysiology and tillering patterns is consistent with results from agronomic field studies. In years when rainfall does not limit growth, resting pastures from late spring until the end of summer or early autumn can lead to an increase in the size, density and vigor/competitive ability of the perennial species, with seedling recruitment contributing to population growth. In drought years, a decline in the perennial species populations may occur—but to a lesser extent when pastures have been rested from grazing over summer than when they have been grazed continuously or grazed using a rigid rotation (L'Huillier and Aislabie, 1987; Hume and Barker, 1991; Kemp et al., 1997, 2000; Nie et al., 1999).

The response of a pasture to a deferred period will depend on the botanical composition at the time of stock exclusion, the seasonal conditions, soil fertility, and the opportunities for recruitment (Garden et al., 2000). In New South Wales, Australia, it was shown pasture rest could increase the content of perennial species and reverse pasture decline, with the rate of response depending on the proportion of perennial species initially present

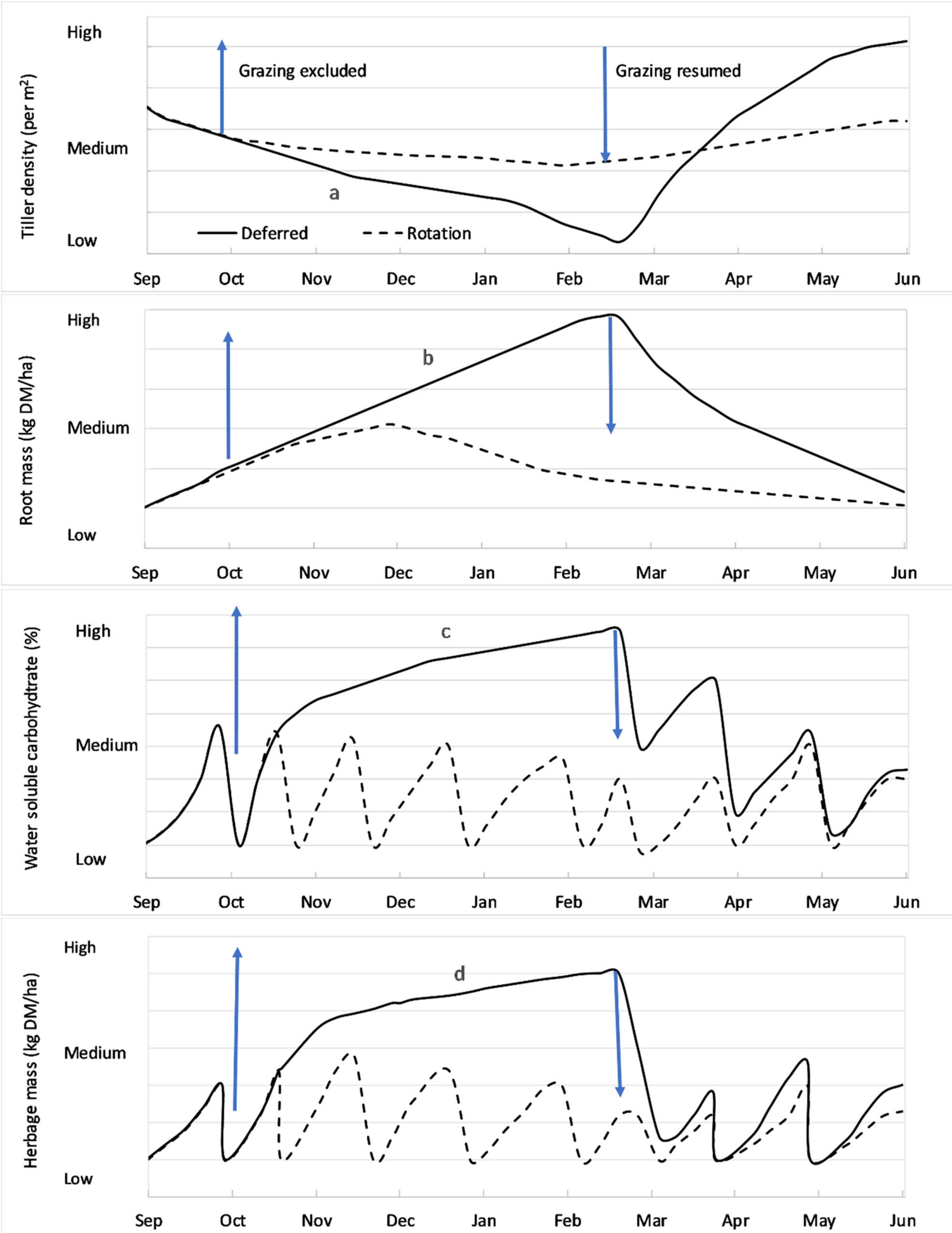

FIGURE 1 | Continued

FIGURE 1 | Changes in *L. perenne* tiller densities, root mass, water soluble carbohydrate content and available herbage in a *L. perenne*-based pasture in response to rotational grazing '- - - -'; or deferred grazing (i.e., rotational grazing with a rest period between mid-spring and the end of summer) "______" in a high abiotic (e.g., drought) or biotic (e.g., invertebrate pest) stress environment (based on Lee et al., 2009; Dodd and Mackay, 2011). Arrows denote when grazing is excluded and resumed for the deferred grazing treatment. Grazing intervals will depend on biophysical, climatic and enterprise considerations, but typically range from 3 weeks (during spring) to 10 weeks (during summer/winter). In the deferred pasture there is: (a) a decline in tiller density during the deferred period followed by a rapid increase after grazing is resumed; (b) an increase in root mass during the deferred period followed by a decline after grazing is resumed; and an increase in (c) water soluble carbohydrate and (d) herbage mass during the deferred period followed by fluctuating levels in response to subsequent grazing events.

in the pasture (Dowling et al., 2006). Generally, "*pastures were responsive to rest tactics when the total perennial grass composition was between 10 and 70% irrespective of the perennial grass species, time of year or site. Above 70%, little benefit is likely to be obtained from resting the pastures and if the desirable perennial content is under 10%, it is unlikely to make use of the additional resources made available through a rest period*" (Kemp et al., 2000). In New Zealand, there is a lack of data on these thresholds for perennial ryegrass and how less desirable species, such as *Holcus lanatus* L. and *Agrostis capillaris*, may respond to resting pastures over summer (Garden et al., 2000).

The timing of grazing exclusion and resumption of grazing can have a significant impact on the botanical composition (e.g., Sheath and Boom, 1985). If the grazing is timed for when annual grass weeds are undergoing stem elongation, grazing can remove the developing reproductive stems and prevent flowering and seed production of annual weedy species. If pastures are then immediately rested from grazing until late summer/early autumn, later flowering perennial species can still undergo reproductive development, flower and set seed. This strategy can significantly reduce the content of weedy annual grasses while increasing the perennial content (Nie and Zollinger, 2012). Conversely, when a deferred period is extended into mid- or late-autumn, the accumulated pasture biomass present at the end of summer/early autumn can prevent adequate light from reaching the tiller bases. This can suppress grass tillering and increase mortality of new tillers and seedlings that have emerged from the seedbank. This approach has been suggested to reduce competition from resident species in preparation for oversowing new germplasm in hill country pastures (Nie et al., 1998).

Deferred grazing can have a positive impact on legumes. Increases in the contribution of clover to the sward and greater clover growth rates have been documented in response to deferring pastures from late spring until mid-autumn, with positive effects lasting for several years after the deferred period (Nie et al., 1996). This most likely occurred because deferred grazing reduced the grass tiller density [which was inversely associated with clover growing point density (Nie et al., 1996)]. Changes in the soil microclimate, such as a reduction in the soil surface temperature and increase in soil moisture content (e.g., Tozer et al., 2020), also made conditions more conducive for legume growth (e.g., Suckling, 1959). Conversely, if deferring encourages grass populations, the clover content can be suppressed. This occurred on East Coast New Zealand hill country when pastures were deferred between late spring and early autumn (November—March). The clover content (% of total DM) was reduced, although the mass of legume in the swards was greater in deferred than grazed pastures (Korte and Quilter, 1990). The impact of deferred grazing on clover is also likely to depend on clover morphology, as longer grazing intervals favor larger leaved cultivars to a greater extent than smaller leaved cultivars (Edwards and Chapman, 2011).

Impacts of deferred grazing on pasture quality have varied. For example, the proportion of dead matter at the base of the sward and residual herbage mass can increase in response to deferred grazing, which can lead to a reduction in pasture quality (e.g., McCallum et al., 1991). Conversely, improvements in botanical composition through reducing the sward content of annual species and increasing that of perennial species has led to improvements in the nutritive value of pastures and an increase in the livestock carrying capacity (Nie and Zollinger, 2012).

Deferred grazing has improved herbage growth rates after the deferred period which can compensate for the loss of production which occurs when pasture growth rates slow and swards senesce during the deferred period. This has been demonstrated for summer wet and summer dry hill country in New Zealand (e.g., Tozer et al., 2020) and in a Western Australia Mediterranean climate (Proffitt et al., 1993). In Western Australian pastures, where the average annual rainfall was 307 mm and a typical growing season was between May and October, deferred grazing yielded the same quantity of biomass as the grazed control over one growing season. This was despite the deferred pastures having a reduced period available for grazing (Proffitt et al., 1993).

Plant and Soil Interactions

Deferred grazing can increase deep root biomass when compared with intensive grazing (Mackay et al., 1991; Nie, 2011). This can increase plant access to water and nutrients, enhance drought resilience, and reduce nitrate leaching (Bowman et al., 1998; Dunbabin et al., 2003; Durand et al., 2007). The large amount of litter and plant residue material that is trampled into the soil by livestock at the end of the deferred period adds a carbon pulse to the system, which may immobilize soil nitrogen and reduce nitrate leaching losses (Mackay et al., 1991). Consequently, deferred grazing may provide an opportunity for nitrogen conservation in the soil that could be used for pasture regrowth following the deferred period. However, no published literature is available on the effects of deferred grazing on nitrate leaching.

Further, deferred grazing can increase ground cover during and after the deferred period (Nie and Zollinger, 2008), which is an important driver for reducing sediment concentrations in runoff from pastures (Sanjari et al., 2009). Together with the above-mentioned factors this contributes to the regeneration of soil architecture, pore structure and connectivity under deferred grazing (Proffitt et al., 1993). This was observed in a field experiment comparing physical soil properties under deferred and intensive grazing [e.g., decreased bulk density, and increased water infiltration, unsaturated hydraulic conductivity and air permeability (Nie et al., 1997)].

Anecdotally, deferred grazing has been used to increase the soil moisture content of topsoils. The accumulation of dead plant material in combination with reduced transpiration rates of dead rank vegetation are generally thought to reduce water losses. For example, moisture contents were higher under deferred than rotational grazed pastures at a depth of 0–15 cm in the middle of autumn in summer-wet New Zealand hill country (Nie et al., 1997) and 15–30 cm in autumn and winter in summer-dry southern Australian hill country (Nie and Zollinger, 2012). Responses will differ depending on soil type and climate. Increased soil water contents will lower soil temperatures (Watson et al., 1996). This may be exacerbated by shading through taller dead rank plants under deferred grazing. Higher water contents may prevent the occurrence of soil water repellency, a transient soil property correlated with soil water contents that prevents water from infiltrating into the soil (Doerr and Thomas, 2003; Hermansen et al., 2019). This may further reduce runoff and sediment losses (Gillingham and Gray, 2006; Müller et al., 2018). To our knowledge no studies have analyzed changes in runoff response to summer and autumn storms under deferred vs. conventional grazing.

Macro- and Micro-Fauna

Soil temperature and water content are the most important environmental factors affecting microbial growth and activity in soils (Kirschbaum, 1995; Katterer et al., 1998). For example, Baldrian et al. (2010) found that moisture contents were positively correlated with microbial biomass, enzyme activity, and carbon mineralization. Through altering the topsoil microclimate as described above, deferred grazing can also affect microbial activities in the soils, which affects carbon and nitrogen mineralization. Stimulation of soil organic matter mineralization has been observed under deferred grazing (Mackay et al., 1991; Nie et al., 1996).

The accumulation of biomass and changes in microclimate (e.g., increased soil surface moisture and moderation of temperature) that occur when pastures are deferred may change the suitability of habitat for invertebrate pests such as *Costelytra zealandica* (White) (grass grub) (e.g., Watson et al., 1996). This does not appear to be an issue with pastures opened in early autumn, but may become an issue if pastures are opened in late autumn (McCallum et al., 1991; Anon, 2006).

Facial eczema has been flagged as a concern as it often proliferates when litter levels are high. However, *Pseudopithomyces chartarum* (Berk. & M.A. Curtis) Jun F. Li, Ariyaw. & K.D. Hyde spore counts have been lower after deferring than in grazed pastures (Suckling, 1959; McCallum et al., 1991). The reasons for the potentially lower spore counts are not known and require research.

At a landscape scale, the effects of deferred grazing on nitrogen losses via leaching, and phosphorus and sediment losses via runoff and erosion are largely unknown. While, based on first principles, it is assumed that the risk of nutrient and sediment losses will be reduced due to improved ground cover, greater rooting depth, enhanced soil structural stability and nitrogen immobilization, no studies have been conducted to quantify these potential benefits at larger scales. Further, the implications of deferred grazing management for a farm's overall feed supply and its environmental footprint have not been assessed. At a farm-scale, a critical issue is how to guarantee a sufficient supply of high quality feed throughout the year with a low environmental impact. A strategic integration of deferred grazing into a farm system would provide standing forage in late summer/early autumn while enabling feed to accumulate in the paddocks on the rest of the farm. The additional pasture may reduce farmers' reliance on crops to address feed shortages in late autumn and early winter. This could lead to additional environmental benefits through reducing soil cultivation/disturbance, lowering energy consumption and thus greenhouse gas emissions and lowering the risk of nutrient losses to waterways through runoff and erosion.

WOODY SPECIES AND THEIR USES IN FARMING SYSTEMS

The Role of Woody Vegetation

Woody vegetation is almost always a component of farming enterprises throughout New Zealand, on flat to steep land, and at a range of scales. About 11.4 M ha of the country's 26.4 M ha land area are used for pastoralism involving grazing livestock, mostly sheep and beef cattle (8.5 M ha) and dairy cattle (2.6 M ha) (White, 1999; Anon, 2018). The woody component ranges from individual trees and isolated patches or fragments of indigenous (native) species through to introduced (exotic) shrub and tree species, and mixtures of natives and exotics, for a range of purposes (Wilkinson, 1999; Walker et al., 2004; Dodd et al., 2008; Benavides et al., 2009). Native shrub and tree species are also being planted increasingly at strategic locations within farms (Marden et al., 2005; Dodd and Ritchie, 2007; Tane'sTreeTrust, 2011; Norton et al., 2018), and this trend is expected to continue.

The country's forestry estate is 8.1 M ha, 30% of New Zealand's total land area, and comprises about 1.7 M ha of exotic species in production forestry, about 90% of which is *Pinus radiata* D. Don; native forests cover 6.4 M ha, with 1.2 M ha of these being owned privately (MPI, 2019, 2020). On land > 20° slope, pastoralism and production forestry are frequently competing land uses with the balance between them being influenced by factors including temporal and spatial economics, environmental and political issues and concerns, and rural and community vitality (Douglas et al., 2013b). Ingress and development of woody weed species such as the exotics *Ulex europaeus* L. and *Rubus fruticosus* L., and the native *Leptospermum scoparium* J. R. et G. Forst., can occur on farm land principally because of reduced soil nutrient status/fertilizer inputs and lowered livestock grazing pressures (MacCarter and Gaynor, 1980; Bascand and Jowett, 1982; Bourdôt et al., 2007; Douglas et al., 2015).

Integrating woody exotic and native vegetation into farming systems has numerous potential benefits including provision of shade and shelter for grazing livestock (Gregory, 1995; Hawke and Dodd, 2003; Pollard et al., 2003), enhanced plant and faunal biodiversity (Blackwell et al., 2008; Griffiths et al., 2008; Norton et al., 2018), soil improvement through decomposition of leaf litter and roots, N from legumes and increased soil nutrient levels (Hawke and O'Connor, 1993; Benavides et al., 2009; St. John et al., 2012), and vista enhancement (Swaffield and McWilliam, 2013). Other benefits include increased carbon sequestration (Czerepowicz et al., 2012; Dymond et al., 2013; Mason et al., 2014) although effects on soil carbon mass vary with species (Douglas et al., 2020), fodder for honey bees (*Apis mellifera* L.) (Butz Huryn, 1995) and birds (MacFarlane et al., 2016), provision of high-value honey (Stephens et al., 2005; Martini, 2016), specialty timbers and other products such as edible nuts (Davies and Macfarlane, 1979; Bull et al., 1985; Davies, 1985b), feedstocks for bioenergy production (Snowdon et al., 2013), and remediation of heavy metal contaminants from soil and groundwater (Robinson et al., 2000; Hahner et al., 2014).

A widespread function of woody vegetation is erosion control, principally of mass movement processes, but also of other types such as surface erosion (wind and mediated by water) and streambank erosion (Pollock, 1986; van Kraayenoord et al., 1986; Bergin et al., 1995; Hicks, 1995; Cairns et al., 2001; Marden et al., 2005; Hughes, 2016). Wide-spaced trees of *Populus*, *Salix*, *Eucalyptus* and other species enable pastoralism to continue on steep, erodible slopes (Thompson and Luckman, 1993; McIvor et al., 2011; Douglas et al., 2013a). Associated with erosion control is the control of stocks and flows of sediments, nutrients and faecal contaminants (Parkyn et al., 2003; Davies-Colley, 2013; Dodd et al., 2016). Regardless of species, woody vegetation has greater vertical and lateral root system development than herbaceous species, conferring increased soil stabilization on slopes and control to greater soil depth (Stokes et al., 2009).

Woody Species for Fodder

The potential of woody species to supply supplementary fodder for grazing livestock in New Zealand's farming systems, particularly those located in areas or regions where pasture production and quality are reduced because of environmental limitations such as soil water deficits, has been recognized for a number of decades (Halliwell, 1979; Davies, 1985a; Sheppard, 1985; Lambert et al., 1989a; Wills et al., 1990; Douglas et al., 1996b; Charlton et al., 2003). Target regions for using woody species for fodder are mainly those on the east coast of the country, extending in the North Island from Northland to Wairarapa, and in the South Island comprising principally Marlborough, Canterbury and Central Otago, the latter of which has a semi-arid climate with annual rainfall of <400 mm (Macara, 2015). Management of individual species has been based mainly on growth form, particularly canopy height, and annual and seasonal growth patterns, and ranged from direct grazing, coppicing and pollarding to grazing-cutting combinations. Canopies of species have been defoliated once or more per year or stock-piled for use in subsequent years depending on livestock feed requirements (Lambert et al., 1989d; Douglas et al., 1996a). The main woody species in New Zealand with potential to supply fodder for livestock (i.e., that can be grown in blocks or grazed directly) are presented in **Table 2**.

Exotic Species

Until the early 2000s, most attention was given to *Cytisus proliferus* var. *palmensis* (henceforth *C. proliferus*) (Radcliffe, 1985; Townsend and Radcliffe, 1987, 1990; Lambert et al., 1989a; Borens and Poppi, 1990; Douglas et al., 1998). In Canterbury under grazing by sheep and trimming, or cutting only, edible yield (leaf and stem < 6 mm diameter) of plants cut later to 0.5 m, when aged 27 months, averaged 2,130 g DM per plant (Radcliffe et al., 1985). Under a range of cutting and grazing treatments, the highest yields of 330–450 g edible DM (EDM)/plant/year were obtained under cutting (Townsend and Radcliffe, 1990). On two hill sites in Canterbury, mean yield of cut plants was 940 and 1,080 g EDM/plant/year (Radcliffe, 1986). Variation in edible yield between plants at the hill sites and that at the other sites was attributed to numerous factors including differences in incidence and severity of frosts, soil type, and plant layout/spacing. Assuming 7,500 plants/ha, annual yields of 2.5–3.4 t EDM/ha were estimated by Townsend and Radcliffe (1990) for the most productive treatment, which provided additional DM of up to 22% over pasture alone.

The leaves of *C. proliferus* are very palatable, have crude protein content of 170–260 g/kg DM depending on leaf age and other factors, and in trials with lambs, *in vivo* digestibility of DM (DMD) was 77% and organic matter digestibility (OMD) was 78% (Borens and Poppi, 1990). In the lower North Island, estimated *in vivo* DMD was 71–73% (Lambert et al., 1989c) and *in vitro* OMD attained 77-85% (Douglas et al., 1996a). Over 6 weeks, average growth rate of lambs browsing *C. proliferus* (81 ± 36 g/day) was less than for those grazing *Medicago sativa* L. (265 ± 33 g/day) and *Bromus catharticus* Vahl (151 ± 35 g/day), suggesting that the feeding value of the species was low compared with well-managed pastures (Borens and Poppi, 1990). In Australia, high concentrations of phenolic compounds in summer and autumn (5–6% of DM) reduced palatability and feed intake compared with in winter (< 3% of DM) (Wiley, 2006); aspects which have not yet been studied in New Zealand. The foliage contains marginal or low levels of phosphorus and sodium, but in a pasture-tagasaste system it is possible that grazing livestock will meet their requirements through pasture intake. Management of *C. proliferus* should aim to reduce bark-stripping and keep canopies within stock grazing height and it should be used on drier sites to reduce susceptibility to collar rot (Lambert et al., 1989d).

Species of *Dorycnium*, principally *D. hirsutum* and *D. pentaphyllum* Scop., were first evaluated for revegetation and fodder supply in the 1970s in semi-arid country and rangelands in the South Island and later in the North Island (Wills, 1983; Sheppard and Douglas, 1986; Wills et al., 1989, 1999; Douglas et al., 1996b). They were found to be very drought- and frost-tolerant and tolerant of hard grazing once established. Accessions of *D. pentaphyllum* were more palatable to sheep than those of *D. hirsutum*, although there was considerable variation between accessions of *D. hirsutum* in browsing preference depending on location and browsing time (Wills et al., 1999), and perhaps variation in hairiness and leaf chemical composition. Under very dry conditions, accessions of *D. pentaphyllum* wilted earlier than

TABLE 2 | Characteristics of exotic and native shrubs/trees potentially useful as forage for sheep and beef cattle in New Zealand.

Species	Common name	Environmental tolerances[a]					Growth habit[b]	Growth rate[c]	Palatability[d]	Toxicities[e]	Tolerance to defoliation[f]	Weed risk[g]	Seed availability[h]	References
		Drought	Frost	Dampness	Wind	Salt spray								
Exotic														
Atriplex halimus L.	Mediterranean salt bush	H	H	L	H	H	E	M	M		M	L	R	Sheppard, 1985; Wills et al., 1990; Wills and Begg, 1992; El-Shatnawi and Turuk, 2002; Walker et al., 2004; Ortiz-Dorda et al., 2005; Heuzé et al., 2019
Ceanothus griseus (Trel. ex B.L.Rob.) Mc Minn.	Ceanothus, Californian lilac	H	M	L	H	H	E/NF	S	M		M	L	R	Sheppard, 1985; Lambert et al., 1989a,b; Pande, 1990; Paine et al., 1992; ElNativoGrowers, 2020
Cytisus proliferus L. f. var. *palmensis* Christ	Tagasaste, tree lucerne	H	M	L	H	M	E/NF	F	H		M	M	C	Davies and Macfarlane, 1979; Sheppard, 1985; Snook, 1986; Lambert et al., 1989a,b,c; Borens and Poppi, 1990; Townsend and Radcliffe, 1990; Douglas et al., 1996a, 1998
Dorycnium hirsutum (L.) Ser.	Hairy canary clover	H	H	L	M	H	E/NF	S	L		L	L	R	Wills et al., 1989, 1999; Heenan et al., 1998; Lane et al., 2004; Bell et al., 2008
Gleditsia triacanthos L.	Honey locust	M	H	M	M	M	D/NF	M	M		H	H	R	Davies and Macfarlane, 1979; Halliwell, 1979; Davies, 1985a; Baertsche et al., 1986; Blair, 1990; Gold and Hanover, 1993; Heenan et al., 1998; Anon, 2019b; Clothier, 2019
Medicago arborea L.	Tree medick	H	M	L	M	M	E/NF	M	H		M	L	R	Davies and Macfarlane, 1979; Davies, 1985a; Scott et al., 1985; Sheppard, 1985; Lambert et al., 1989a,b; Pande et al., 2002; Douglas et al., 2004; Small, 2011
Robinia pseudoacacia L.	Black locust, false acacia	H	M	M	M	M	D/NF	F	H	Leaves, pods, seeds	H	M	C	Lambert et al., 1989a,b; Barrett et al., 1990; Huntley, 1990; Pande et al., 2002; Anon, 2008, 2014; Mantovani et al., 2014a,b
Salix matsudana Koidz. × *alba* L. clone 'Tangoio'	Hybrid tree willow	M	H	H	H	L	D	F	M		H	L	SB	Douglas et al., 1996a, 2003; McIvor et al., 2005; National Poplar and Willow Users Group, 2007; Plant and Food Research, 2013

(Continued)

TABLE 2 | Continued

Species	Common name	Environmental tolerances[a]					Growth habit[b]	Growth rate[c]	Palatability[d]	Toxicities[e]	Tolerance to defoliation[f]	Weed risk[g]	Seed availability[h]	References
		Drought	Frost	Dampness	Wind	Salt spray								
Salix schwerinii E. L. Wolf	"Kinuyanagi," Japanese fodder willow	L	H	H	M	L	D	F	M		H	L	SB	Douglas et al., 1996a; Charlton et al., 2003; McIvor et al., 2005; National Poplar and Willow Users Group, 2007; Plant and Food Research, 2013; Salam et al., 2015
Native														
Coprosma repens A. Rich.	Taupata, mirror bush	M	M	L	H	H	E	M	M		H		C	Wright and Cameron, 1985; Pollock, 1986; Dodd and Ritchie, 2007; Anon, 2020a
Coprosma robusta Raoul	Karamu	M	M	M	M	M	E	M	M		M		C	Allen et al., 1984; Pollock, 1986; Bannister and Lee, 1989; Wilson, 1994; Thomson, 2011; de Lange, 2021
Cordyline australis (G.Forst.) Endl.	Cabbage tree, ti kouka, palm lily	M	H	H	H	M	E	M	M		H		C	Pollock, 1986; Harris and Mann, 1994; Harris et al., 2001, 2003; Anon, 2020b
Corynocarpus laevigatus J.R. et G. Forst.	Karaka	M	L	L	H	H	E	M	M	Fruit, seeds	M		C	Pollock, 1986; Thomson, 2011; Cope and Parton, 2012; Anon, 2014
Griselinia littoralis Raoul	Broadleaf, kāpuka	M	H	M	H	H	E	M	H		M		C	Pollock, 1986; Timmins, 2002; Sweetapple and Nugent, 2004; Bee et al., 2007; Thomson, 2011; Anon, 2020c; de Lange, 2021
Hoheria populnea (A.Cunn.)	Lacebark, houhere, ribbonwood	M	M	M	M	L	E	M	M		M		C	Pollock, 1986; Thomson, 2011; Anon, 2020d; Nurseries, 2020
Melicytus ramiflorus J.R. et G. Forst.	Māhoe, whitey wood	M	M	M	M	L	E	M	M		M		C	Allen et al., 1984; Pollock, 1986; Timmins, 2002; Sweetapple and Nugent, 2004; Smale and Arnold, 2005; Dodd and Ritchie, 2007; Thomson, 2011
Phormium tenax J.R. & G.Forst.	Flax, harakeke	M	H	H	H	H	E	M	M		M		C	Pollock, 1986; Dodd and Ritchie, 2007; Litherland et al., 2009; Thomson, 2011
Pittosporum crassifolium Banks et Sol. ex A.Cunn.	Karo	M	M	L	H	H	E	M	L		M		C	Wright and Cameron, 1985; Pollock, 1986; Bannister et al., 1995; Weston, 2004

(Continued)

TABLE 2 | Continued

Species	Common name	Environmental tolerances[a]					Growth habit[b]	Growth rate[c]	Palatability[d]	Toxicities[e]	Tolerance to defoliation[f]	Weed risk[g]	Seed availability[h]	References
		Drought	Frost	Dampness	Wind	Salt spray								
Pseudopanax arboreus (Murray) Philipson	Fivefinger, whauwhaupaku	M	M	L	M	L	E	M	M		M		C	Allen et al., 1984; Campbell, 1984; Pollock, 1986; Wilson, 1994; Sweetapple and Nugent, 2004; Dodd and Ritchie, 2007; Anon, 2020e

[a]*Environmental tolerances (based on Pollock, 1986) of established plants.*

Drought:

Low (L): May tolerate 1 or 2 days of low soil water content.
Moderate (M): Can tolerate mild soil water deficits which do not prolong plant wilting.
High (H): Can tolerate extended periods of soil water deficits e.g., weeks to entire seasons.

Frost:

Low: Susceptible to damage from cold winds or light frost e.g., −2°C.
Moderate: Tolerant of frosts as low as −6°C.
High: Frost hardy in areas of lower altitude and will tolerate −7°C or lower.

Dampness:

Low: Will tolerate saturated soils for short periods e.g., 1 or 2 days.
Moderate: Will tolerate frequently wet soils but not for longer than several weeks at a time.
High: Will tolerate continually saturated soil.

Wind:

Low: Susceptible to extensive damage from strong winds.
Moderate: Will tolerate strong to gale force winds, but not continuous wind battering.
High: Will tolerate all wind strengths for prolonged periods with negligible damage to foliage.

Salt spray:

Low: Intolerant of salt on foliage.
Moderate: Tolerates light deposits of salt on leaves, but only for short periods.
High: Tolerates persistent exposure to salt-laden winds and salt deposits on leaves.

[b]***Growth habit***

E, evergreen; D, deciduous; NF, nitrogen-fixing.

[c]***Growth rate***

Slow (S): Lateral or height growth is <0.3 m per year.
Moderate (M): Sites with negligible environmental limitations enable lateral or height growth of 0.3–1.0 m per year.
Fast (F): Rapid growth under optimum conditions e.g., > 1 m height growth per year for taller species.

[d]***Palatability [of foliage (leaf + soft stem)]***

Low: The presence of physical, chemical or other plant factors discourages but does not prevent consumption by livestock.
Moderate: Foliage is likely to be a regular component of the diet, but not exclusively.
High: Plants are readily consumed by livestock, with most or all foliage removed.

[e]***Toxicities (in plant parts)***

Plant parts known to be poisonous—otherwise left blank; the effect on livestock will depend partly on the proportion of the poisonous component in the overall diet.

[f]***Tolerance to defoliation***

Low: Partial defoliation e.g., <50% canopy removal, significantly impairs plant vigor and results in very slow regrowth and sometimes plant death.
Moderate: Tolerates wider range of partial defoliation and usually results in healthy regrowth.
High: Can defoliate partially (> 50%) or sometimes completely and expect healthy, vigorous regrowth; may be able to defoliate two or more times per year.
Responses to defoliation by livestock may be different to those from cutting/pruning and will vary with plant age/size and other factors.

[g]***Weed risk (only for exotic species in New Zealand)***

Low: Negligible spread by natural reproductive or vegetative mechanisms, or low potential to establish in new areas e.g., because of poor seedling vigor, low competitive ability.
Moderate: Able to spread several meters or more beyond planted or sown sites within a few years.
High: Potential to be highly invasive and spread widely by propagule dissemination by wind, birds or other methods; high re-establishment potential in areas of low ground cover.

[h]***Seed availability***

Restricted (R): Usually unavailable from commercial outlets in New Zealand, requiring field collection, sourcing from germplasm center, or importation.
Commercial (C): Available from one or more commercial outlets in New Zealand.
Stool blocks (SB) in New Zealand.

those of *D. hirsutum*. In the early 2000s over two consecutive years, seed multiplication of an elite selection of *D. hirsutum* was attempted but it failed because of unusually moist conditions. *Dorycnium rectum* (L.) Ser. in DC. is palatable but its leaves have very high concentrations of condensed tannins (19% of DM), with consequent low DMD (60%) (Waghorn et al., 1998), and it has very low productivity in dry environments (Douglas et al., 1996a).

Early observations of *Atriplex halimus* found its foliage to be very palatable but plants grew poorly on hills in Marlborough and near Christchurch (Sheppard, 1985). At other locations in the South Island, the species was more adaptable to cold, dry, hill country than other species of *Atriplex* resulting in >20 ha of *A. halimus* being established on one farm and thousands of seedlings being produced for planting in the early 1990s (Wills et al., 1990; Wills and Begg, 1992). *Atriplex* spp., likely including *A. halimus*, were evaluated in at least two regions in the North Island, but results were not reported. Foliage of *A. halimus* was found to be highly nutritious with DMD of 78–80%, metabolisable energy content of about 12 MJ/kg DM, and crude protein content of 75–219 g/kg DM (estimated from Table 2 as N concentration × 6.25) (Wills et al., 1990). The most recent report found was the use of *A. halimus* on a commercial farm in Marlborough (Wills, 2008).

Numerous other woody species were evaluated in the latter half of the twentieth century for fodder potential with the most promising being *Ceanothus griseus*, *Gleditsia triacanthos*, *Medicago arborea*, and *Robinia pseudoacacia* (Davies and Macfarlane, 1979; Davies, 1985a,b; Sheppard, 1985). Sheppard (1985) described *C. griseus* and other *Ceanothus* spp. as palatable. *Gleditsia triacanthos*, *M. arborea*, and *R. pseudoacacia* were all regarded as palatable to livestock, productive, and free from disease (Davies, 1985a,b). Shrubs grown in row plots in summer-moist hill country in the lower North Island had mean annual production (g DM/m row) over 2 years in the order *R. pseudoacacia* (315) > *C. griseus* (251) > *M. arborea* (79) and their foliage was highly digestible (*in vitro* DMD) being 70% for *R. pseudoacacia*, 75% for *C. griseus* and 73% for *M. arborea*, compared with 69% for pasture (Lambert et al., 1989c). At the same site, these species were the most preferred of a range of species by grazing sheep and goats (Pande et al., 2002). The relatively low yield of *M. arborea* was because of its inherent canopy size but also possibly low tolerance to the damp conditions at the site, particularly in one of the replicates, or nodulation failure which was suggested as a cause of decreasing plant productivity over 5 years in Canterbury hill country (Radcliffe, 1985). *Robinia pseudoacacia* is the only species known to have toxic elements in the foliage in New Zealand (Anon, 2014), also reported internationally (Anon, 2008).

Since the early 2000s, most research on woody species has focused on the yield and fodder value of *Populus* and *Salix* spp., with nearly all being conducted in the lower North Island. Earlier investigations in the same regions and elsewhere found that *P. deltoides* × *nigra* "Flevo" and *S. matsudana* × *alba* "Tangoio" were palatable to animals, productive and disease-free (Davies, 1985a), and yield of "Tangoio" was greater than for other *Salix* spp. (Radcliffe, 1985). Foliage of *S. matsudana* × *alba* had greater DMD than that of the leafier *S. viminalis* (64 vs. 57%) and its voluntary intake of DM by sheep and goats was greater, possibly because of differences between the species in concentrations of lignin and condensed tannin (McCabe and Barry, 1988). "Tangoio" had greater nutritive value than *S. schwerinii* on summer-moist hill country and on drought-prone sands in terms of *in vitro* OMD (64–81% vs. 40–62%), lower lignin concentration (59 vs. 95 g/kg DM) (Douglas et al., 1996a), and lower condensed tannin concentration (59 vs. 255 g/kg DM) (Oppong et al., 2001), and it was more drought-tolerant (Douglas et al., 1996a).

The promising characteristics of "Tangoio" led to the establishment and management of browse or coppice blocks of the clone (Douglas et al., 2003; National Poplar and Willow Users Group, 2007) and research on their potential for improving livestock performance during summer drought. Consuming foliage of the clone reduced liveweight loss of ewes and beef cattle and maintained or increased ewe reproductive performance during pre-mating and mating periods, in comparison to stock grazing "drought pasture" (Moore et al., 2003; McWilliam et al., 2005; Pitta et al., 2007). "Tangoio" has potential to reduce methane emissions in ruminants (Ramírez-Restrepo et al., 2010) and may benefit hoggets with parasite burdens (Musonda et al., 2009), possibly because of the type and concentration of its foliar condensed tannins. Supplementing pasture with *P. deltoides* × *nigra* "Veronese" has also increased ewe reproductive performance (McWilliam et al., 2004).

Annual yield of edible fodder of trees of *Salix* and *Populus* spp. has been estimated for wide-spaced trees and for those in browse blocks. Individual trees of "Tangoio" aged 5–10 years [diameter at breast height (DBH) = 0.09–0.20 m; canopy width 2.3–6.3 m] yielded 3–22 kg DM/tree compared with 1.6–18.0 kg DM/tree for "Veronese" (DBH = 0.07–0.21 m; canopy width 2.2–4.2 m) (Kemp et al., 2001) and over a greater range of tree age/size, exponential relationships were developed between edible fodder and diameter at breast height (Kemp et al., 2003). With knowledge of tree stocking rate, these data enabled estimation of yield on a per hectare basis for feed budgeting. In browse blocks involving *Salix* spp., edible yield has been up to 7.0 t DM/ha/year in established stool blocks (Jones and McIvor, 2013), although this can vary considerably with tree density and planting arrangement.

Native Species

Almost no research has been conducted on the potential of native woody species to supply fodder for livestock in farming enterprises, including on annual and seasonal production, nutritional characteristics (palatability, digestibility, and nutrient contents), livestock performance, and optimum grazing/cutting management for the benefit of the plants and the stock that graze them. A notable exception is the research conducted on *L. scoparium* and *Cassinia leptophylla* (Forst.f.) R.Br. on summer-moist hill country in the 1980s (Lambert et al., 1989a), which found that both species had low potential as fodder sources. *Cassinia leptophylla* was unpalatable to sheep and goats and *L. scoparium* was intolerant of defoliation and its foliage had low palatability and digestibility (Lambert et al., 1989d).

In an analysis of preferences by deer for shrub and tree species, those such as *Aristotelia serrata*, *Coprosma grandifolia*, *Cordyline australis*, *Griselinia littoralis*, *Melicytus ramiflorus*, and *Pseudopanax arboreus* were preferred, but most species were not selected, or avoided. Preferred species had relatively low (<4 g/kg DM) foliar lignin concentration (Forsyth et al., 2002). In addition to concentrations of cellulose and phenolics, Bee et al. (2011) concluded that season and associated species can also influence diet selection. Exclusion of cattle in forests in Westland resulted in an increase in abundance of woody species (Buxton et al., 2001) and where sheep and cattle were excluded from forest fragments in the Waikato region, abundance of woody species including *Coprosma grandiflora*, *Schefflera digitate,* and *M. ramiflorus* increased (Burns et al., 2011). The preference of species to ruminants was categorized by Sweetapple and Nugent (2004) who found that highly preferred species included *C. grandiflora*, *Coprosma lucida*, *G. littoralis*, *M. ramiflorus*, and *S. digitata*. New Zealand's *Carmichaelia* spp. are regarded as highly palatable to many introduced herbivores including sheep, deer and goats (Dawson, 2016). Smale et al. (2008) reported that the palatability of seedlings of tree species to sheep was unknown.

There are numerous anecdotal reports on the palatability of native species to livestock with one of the most recent describing *G. littoralis*, *M. ramiflorus*, *Phormium tenax,* and *P. arboreus* as being moderately to highly palatable (Clothier, 2019). Under the heading of "Stock Fodder Use," species listed as beneficial to stock were *A. serrata*, *C. grandifolia*, *C. robusta*, *Hebe stricta*, *Hoheria populnea,* and *P. tenax* (Dodd and Ritchie, 2007), which implied that they were palatable to varying extents.

The regrowth responses of native woody species to grazing by livestock in terms of morphology and growth rate are unknown or uncertain and often subjective, and no studies have been conducted involving the key potential candidates reviewed here. An indication of potential responses can be gleaned from brief descriptions from nursery growers, for example Anon (2020a,c), on responses likely from coppicing, pollarding or form pruning.

With the (social/political/market) expectation that farm systems and enterprises become more environmentally sustainable, and with increasing recognition that a number of native species have fodder potential, there is an urgent need to progress on research on this largely untapped resource.

IMPLEMENTATION IN FARM SYSTEMS

The previous sections have explored two approaches to a departure from conventional New Zealand pasture management. Deferred grazing departs from the norm in that, while pasture remains the core forage base, the focus shifts from maximizing animal intake efficiency in the short term, to maintaining pasture botanical composition, feed quality and resilience in the longer-term (Da Silva et al., 2004; Nie and Zollinger, 2012). This is achieved by recognizing the importance of tiller demography and reproductive physiology in our primary perennial pasture species. Little is known about the establishment and management requirements of forage shrubs and trees. Woody forages depart from the norm in that they provide an additional forage resource with quite different plant functional traits. This is achieved by exploiting the vertical dimension to the under-utilized resources available in grassland systems—light and space above-ground and soil moisture and nutrients below-ground (Dodd et al., 1998).

While there is a substantial body of literature exploring the dynamics of these two approaches as components of a farm system, there is less consideration of their impact on the whole system. However, some relevant points have been made. Deferred grazing could be used to maintain pasture quality over the whole farm in sheep, beef and dairy systems throughout New Zealand, by removing a proportion of the paddocks from the grazing round and thus increasing grazing pressure on the remaining paddocks. This generally coincides with the spring surplus when there is feed in excess to requirements, which then becomes a challenge in terms of maintaining feed quality for young livestock (Sheath and Boom, 1985). This was demonstrated in East Coast North Island hill country by Suckling (1959), who found that deferring a proportion of the farm enabled the remainder of the feed to be adequately controlled. The utilization of the deferred pastures at the end of summer also allows the covers to increase on the remainder of the farm. This assists in filling the late autumn / winter feed gap when pasture growth rates are often low and there is insufficient pasture available to meet livestock demand. Livestock generally find it more difficult to remove poor quality herbage from steep than easy country. For this reason Sheath et al. (1984) recommend that priority be given to "*control of steep land during late spring-early summer, because of likely longer-term benefits in pasture composition, density and production*." Deferred grazing can assist in controlling pastures on steep hill country farms. By deferring some paddocks and reducing the area available for grazing, the stocking rate is effectively increased on the rest of the farm. This enables the feed supply to better match feed demand and pasture quality to be maintained.

In dairy systems, a short deferred period, in which *L. perenne*-based pastures were allowed to flower followed by hard grazing by dairy cattle, led to increased DM production in the spring during the deferred period by 24% and the summer-autumn following the deferred period by 22%. This resulted in increased milk solids production of about 11.5% per cow (Da Silva et al., 2004). Deferred grazing has been found to be more profitable than a traditional hay/silage system (McCallum et al., 1991), although these authors suggested that no more than 10% of the dairy farm should be deferred in a year. This method of storing and making available standing feed also lowers the carbon footprint by reducing or eliminating the need for machinery and other energy inputs that are required to make hay or silage.

The benefits of these two approaches have been outlined in sections Deferred Grazing and Woody Species and Their Uses in Farming Systems, so why have they not been adopted more widely by New Zealand pastoral farmers? As highlighted, one of the most remarkable features of the New Zealand landscape is the enormous range in environmental diversity within small spatial extents–from soil type, topography and climatic points of view. Thus, it might seem strange that the management of our grazing systems seems to focus on achieving a limited variety of vegetation communities and livestock enterprises.

Part of the reason has to do with the self-identity of New Zealand grassland farmers, who have strong cultural values tied to pasture management and animal husbandry, in the context of a long-held "productivist orientation" (Rosin, 2013). This has been supported by historically high levels of central government investment in relevant research and development (Jacobsen and Scobie, 1999) and the existence of influential supporting organizations such as DairyNZ and non-government organizations (e.g., NZ Grassland Association, NZ Society of Animal Production). Central government subsidies have historically also been important, in that land development grants and minimum price support aimed at increasing foreign exchange earnings (Le Heron and Roche, 1999) were critical in establishing the dominant pastoral vegetation structure as the natural capital base across all types of topography. Maintaining this vegetation structure is predicated on ongoing low-cost inputs of fossil fuel, phosphatic fertilizer and relatively high stocking rates, in an environment that would naturally revert to woody vegetation, including a range of undesirable plants (Bergin et al., 1995; Williams, 2011).

As noted previously, there has historically been strong emphasis on the efficiency of forage utilization in grazing systems. This has been supported by a wealth of research into grazing management and both animal and plant genetic improvement. The two approaches we have discussed inevitably challenge that focus. Deferred grazing at first glance creates the impression of unutilized feed and the development of low quality pasture, while woody forages at first glance creates the impression of lost grazing opportunity during relatively slow establishment, shading of productive pasture and providing a low quality feed (Dodd et al., 2005). In addition, the combination of two forage resources with differing optimal management creates a problem for free-range animal systems.

Overcoming these first impressions, be they real or imagined, is the role of research. However, there are strong causal loop processes operating within the research community that tend to positively reinforce investment in improvements to existing systems (where the value proposition for research is readily quantifiable) and negatively suppress investments in understanding the dynamics of alternative systems (Turner et al., 2016). Hence, the quantum of research and extension activity in components such as deferred grazing and woody forages is orders of magnitude lower than that in conventional pasture management.

In addition, the generation of new understanding through research is likely insufficient to achieve wider uptake. Extension research has highlighted a range of barriers to the uptake of new technologies in agricultural contexts, including issues such as complexity, compatibility with identity and objectives, flexibility, value add, capital outlay, uncertainty, and physical and social infrastructure requirements (Vanclay, 2004). Local studies confirm the role of cost, perceptions of value add, complexity, learning requirements and compatibility with objectives as barriers to the uptake of environmental management practices (e.g., van Reenen, 2012). Farmer adoption of new technologies and practices, and acceptance of risk are linked to age demographics (Brown et al., 2019), thus responsiveness to wider societal expectations will be a generational process. In New Zealand one of the most powerful pathways to adoption is exemplars—farmers follow closely what other farmers are doing and learn rapidly from their peers (both in terms of what to try and what to avoid).

Acknowledging that, key questions for research to answer in gaining a better understanding of these alternative approaches include effects on pasture botanical composition and feed quality, secondary benefits for soil and water quality, biophysical pasture-tree interactions, optimal browse management, and long-term cost-benefit data. Development of supporting technologies out of the R&D community could include virtual fencing, low-cost tree protectors and drones to assist in the establishment of tree seedlings in difficult to access hill country. These enable much more spatially explicit control of grazing to: (1) define deferred areas without additional fencing; (2) ensure livestock graze deferred areas upon re-opening; (3) protect establishing shrubs while utilizing understory pasture; and (4) separate the timing of shrub browsing and interstitial pasture grazing.

Beyond answering component questions outlined above, how would these fit into existing grazing systems?

Deferred grazing is easy to implement, with no capital outlay, and can be implemented anywhere on-farm. The main considerations will be an assessment of which paddocks have an appropriate threshold of desirable species and will benefit most, in terms of improving sown species content, and how to overcome the short-term feed supply/demand imbalance (McCallum et al., 1991). Also, the timing of the deferred grazing period (i.e., opening and closing the gate) is critical and requires an understanding of the lifecycle of desirable and weedy species. In most New Zealand hill country environments, the late spring/early summer period has been characterized by high pasture growth rates and a burgeoning feed surplus (Radcliffe, 1982), hence removing paddocks from grazing is a sensible tactic for improving the level of grazing control on the rest of the farm. However, many intensive systems are now stocked to levels where demand exceeds supply year-round, with the shortfall made up from what used to be known as supplementary feed (Clark et al., 2007). Hence, the short-term loss of pasture-based supply must be made up from additional bought-in feed, or lower production levels accepted. Therefore, in intensive systems, the decision around what area to defer will be a trade-off of the long-term pasture quality benefit and the short-term cost.

Browse shrubs are somewhat more challenging, both in terms of the new knowledge around species selection, establishment and management at the component level, and at the systems level such issues as the additional equipment potentially needed, an understanding of optimal locations for implementation within the system, animal health and welfare implications. Similarly, the question of how much area to devote to browse shrubs applies, which could be addressed by modeling. While component-based models of the interactions between woody plants and understory forage exist, these are not incorporated into the current suite of mainstream farm systems models in New Zealand. However, such models have been developed overseas (e.g., Monjardino et al., 2010).

Ultimately, greater uptake of these two alternative landscape components in hill country grazing systems will be a function of how well they can be shown to deliver to a range of secondary objectives within farm systems (water quality, soil structural stability, landscape and species diversity) while simultaneously maintaining or enhancing the value from livestock enterprises, via feed quality, pasture persistence, feed supply and animal welfare. In other terms, how they can enhance the quantum and balance of all relevant ecosystem services.

RECOMMENDATIONS

On the basis of the discussion in this paper, we offer the following recommendations for research and practice for achieving a step-change in the management of New Zealand's hill country forage base consistent with the concept of increasing the diversity of landscape structure and function.

1. Additional research into the environmental benefits of deferred grazing practices, specifically the reduction of sediment and nutrient losses to water resources through runoff and leaching.
2. More widespread adoption of deferred grazing as a tool to control pasture quality over the whole farm and to increase pasture resilience—particularly where pastures are subjected to multiple and simultaneous stresses (such as drought, invertebrate pest predation and overgrazing).
3. More widespread adoption of proven exotic woody species as multifunctional plants—providing forage, soil structural stability, shade and shelter (and potentially additional biological N-fixation), and other ecosystem services (e.g., vista enhancement, increased carbon sequestration, pollination, nectar source for birds, habitat for invertebrates and birds).
4. Additional research effort into the benefits of woody shrubs for animal welfare and reduction of sediment delivery to waterways.
5. Additional research effort into the potential use of native woody plants in similar ways to those acknowledged and proposed for exotic species.
6. Development of models to explore the interactions between woody plants and understory forages and their impact on New Zealand hill country farm systems.

AUTHOR CONTRIBUTIONS

KT, GD, MD, and KM: design, writing of sections, reviewing, editing, and proofing. All authors contributed to the article and approved the submitted version.

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REVIEW
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Reconnecting Grazing Livestock to Crop Landscapes: Reversing Specialization Trends to Restore Landscape Multifunctionality

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Closely integrated crop and livestock production systems used to be the rule in agriculture before the industrial revolution. However, agricultural landscapes have undergone a massive intensification process in recent decades. This trajectory has led to uniform landscapes of specialized cropping systems or consolidated zones of intensive livestock production. Loss of diversity is at the core of increasing side effects on the environment from agriculture. The unintended consequences of specialization demand the reconciliation of food production with environmental quality. We argue that the reconnection of grazing livestock to specialized crop landscapes can restore decoupled biogeochemical cycles and reintroduce the necessary complexity to restore ecosystem functioning. Besides, the reconnection of crops and livestock promotes several ecosystem services underlying multifunctionality. We focus on the capacity of integrated crop-livestock systems to create biophysical and socioeconomic resilience that cope with weather and market oscillations. We present examples of redesigned landscapes that leverage grazing animals to optimize food production per unit of land while mitigating the externalities of specialized agriculture. We also debate mindset barriers to the shift of current specialization trends toward the design of multifunctional landscapes.

Keywords: biodiversity, ecosystem services, foodscapes, integrated crop-livestock systems, mixed crop-livestock, resilience

INTRODUCTION

Multifunctional landscapes are those providing multiple ecosystem services (ES) simultaneously (Lovell and Johnston, 2009; Butterfield et al., 2016). By balancing the delivery of provisioning, regulating, supporting and cultural ES, the promotion of landscape multifunctionality is critical to ensure the sustainability of "working lands" (*sensu* Kremen and Merenlender, 2018) and human well-being (Millennium Ecosystem Assessment, 2005; Butterfield et al., 2016; Wood et al., 2018; Fagerholm et al., 2020). However, agricultural landscapes have undergone the opposite trend in the last decades. The introduction of high yielding crop cultivars, the growing use of chemicals (inorganic fertilizers, herbicides and pesticides) and the development of high-tech machinery have resulted in an intensive, specialized farming model that has been successful in maximizing single ES (e.g., food production) but often at the expense of other fundamental ES, such as biodiversity and climate regulation (Tilman et al., 2001; Foley et al., 2005; Kremen and Merenlender, 2018).

The reduced diversity and increased uniformity perceived nowadays in agricultural landscapes are often a result of the spatial decoupling between crop and livestock production (Lemaire et al., 2015). For millennia, the fluxes connecting them—such crop residues being used to feed livestock and animal manure serving as the main nutrient source for crop production—were fundamental to sustain food production in ancient agricultural societies (Russelle et al., 2007; Bogaard et al., 2013). Since the "Green Revolution," however, specialized cropping systems have increasingly encroached upon natural ecosystems worldwide, as reported in the *Rio de la Plata* grasslands region of South America (Modernel et al., 2016; de Faccio Carvalho et al., 2021). Ruminant livestock production, in turn, has moved from extensive grazing systems to feedlots, or concentrated in pasture areas under increased stocking rates, frequently resulting in overgrazing (de Faccio Carvalho and Batello, 2009; Modernel et al., 2016). The creation of these consolidated zones of specialized production has resulted in loss of diversity and agroecosystems multifunctionality, besides environmental issues such as water contamination and atmospheric pollution (Verhoeven et al., 2006; Gerber et al., 2013).

The reconnection of crop and livestock production in integrated crop-livestock systems (ICLS) has been proposed as an alternative to the kind of specialized agricultural production that results in landscape uniformization, simplification of ecological processes and heavy reliance on external inputs (Russelle et al., 2007; FAO, 2010; Lemaire et al., 2015). In his framework inspired by the classic paper "The Strategy of Ecosystem Development" (Odum, 1969), Tracy (2007) identified modern cropping systems based on monocultures as an example of a young, developing ecosystem: "*highly productive and biologically simple, but generally unstable and leaky from a mineral cycling perspective.*" In contrast, mature ecosystems are "*more stable and retentive of soil nutrients*" and "*although less productive, [they] provide many valuable ecosystem services we depend on to maintain a high quality of life*" (Tracy, 2007). In this sense, although modern agriculture has been successful in maximizing food production, mankind also depends on several other ES to thrive, and those are usually provided by mature ecosystems. Thus, reconciling these demands is a challenge. For containing elements of both, ICLS represent a good compromise between developing ecosystems and mature ecosystems: high productivity, conferred by the production of crops and livestock, and a wide range of ES emerging from the complex interactions and synergies between system components (Tracy, 2007).

In this manuscript, we present the benefits from reconnecting grazing livestock to previously uniform crop landscapes as an alternative to restore the multifunctionality lost over decades of agricultural specialization. We present this framework by exploring the effects of grazing livestock integration across different spatio-temporal scales and with different levels of planned biodiversity as pivotal to the design of future multipurpose foodscapes (i.e., the landscapes providing humans and herbivores with nourishment). We also address barriers and levers in socialscapes (i.e., communities and cultures in close relationship with foodscapes) that are important to take into account in the design of agricultural systems where grazing livestock share space with crops in valuable cropping areas.

RESTORING LANDSCAPE MULTIFUNCTIONALITY: PLANNED BIODIVERSITY RECONNECTING GRAZING ANIMALS TO CROP LANDSCAPES

Rethinking agriculture to shift the focus from the production of single ES back to a multifunctional perspective where key ES are integrated (e.g., provision of quality food and water, carbon sequestration, and promotion of biodiversity above and below ground) is critical to ensure that food production systems will be able to feed a growing human population. Besides, climate change and its associated uncertainties exacerbate the need for resilient food systems (Foley et al., 2011; Kremen and Merenlender, 2018; Wood et al., 2018). Therefore, considering that biodiversity loss is a major driver of reduced multifunctionality across all terrestrial ecosystems (Cardinale et al., 2012; Fanin et al., 2018), biodiversity-based, resilience-oriented farming practices must be targeted if the aim is to restore landscape multifunctionality (Foley et al., 2005, 2011; Kremen and Merenlender, 2018). Alternatives for the re-diversification of agricultural systems with associated gains in ES delivery include the use of diversified crop rotations or polycultures (Kremen and Merenlender, 2018; Bowles et al., 2020; Guzman et al., 2021), cover crops (Pinto et al., 2017; Sekaran et al., 2021; Villarino et al., 2021) and the recoupling of crop and livestock production (Soussana and Lemaire, 2014; de Faccio Carvalho et al., 2021; Sekaran et al., 2021).

Increased crop rotation diversity (or "planned biodiversity," defined as the biodiversity chosen by the farmer; Brustel et al., 2018) has been recognized for improving crop yields (Bowles et al., 2020) and stability in the face of climatic oscillations (Gaudin et al., 2015; Bowles et al., 2020). These characteristics are critical for food security in the context of climate change. Also, polycultures improve the richness and diversity of soil arbuscular mycorrhizal fungal communities in areas previously managed under intensive monoculture farming, with applications for landscape multifunctionality restoration (Guzman et al., 2021). As part of the "associated biodiversity" (i.e., the component of agrobiodiversity that emerges from farming practices; Duprat et al., 2018), these organisms play an important role in nutrient acquisition, soil structure formation and drought tolerance.

The inclusion of cover crops in agricultural rotations has also been recognized for providing multiple ES, in such a way that these plants have been called "service crops" (Piñeiro et al., 2014; Pinto et al., 2017). Benefits of cover cropping include reduced soil erosion and compaction, weed suppression, improved pollination, nitrogen fixation and reduced leaching, carbon sequestration and accumulation in soils, and improved soil aggregation, water retention and drought tolerance (Tonitto et al., 2006; Piñeiro et al., 2014; Pinto et al., 2017; Reicosky et al., 2021). Examples of cover crops typically used in Latin America include grass species such as oats (*Avena* spp.), Italian ryegrass (*Lolium multiflorum*) and signal grass (*Urochloa* spp.), legumes such as vetches (*Vicia* spp.) and clovers (*Trifolium* spp.), and others. In general, these forage species are chosen because of their biomass production potential and feasibility to no-till systems, which are widely used in many countries.

Despite all those benefits, cover crops lack human-edible food production (de Faccio Carvalho et al., 2018a) and direct economic returns (Wittwer et al., 2017). Furthermore, because crop growers are usually concerned about soil compaction, millions of hectares are cultivated with non-grazed cover crops just in the same period that livestock experience feed shortages in disconnected grazing systems. ICLS, in contrast, can encompass all these alternatives by using diverse cover crops as high-quality forage for grazing. When combined with soil conservation practices such as no-tillage, ICLS can fully exploit the synergisms and emergent properties of the system (de Faccio Carvalho et al., 2010).

Grazing of cover crops in annual or perennial cropping systems is one of the many possible models of crop-livestock integration (Brewer and Gaudin, 2020). Examples based on cover crop grazing range from simpler designs where the same crop rotation takes place repeatedly every year (e.g., soybean production followed by temperate grass cover crops grazed by cattle; de Albuquerque Nunes et al., 2021), to more complex crop rotations with a greater diversity of crop species [e.g., Sudan grass (*Sorghum sudanense*), soybean, maize and rice in the same area in subsequent summers, followed by a mixture of Italian ryegrass + white clover (*Trifolium repens*) grazed in winter; Carlos et al., 2020]. Cover crop grazing in perennial systems is well-represented by grazing of the understory vegetation in orchards (Ramos et al., 2011) and vineyards (Ryschawy et al., 2021). Other ICLS models include stubble grazing (Rakkar et al., 2017), sod-based crop rotations (Katsvairo et al., 2006) and production of dual-purpose crops (Kirkegaard et al., 2012). The possible designs of diverse cropping systems connected with livestock are almost unlimited, expanding across various spatiotemporal scales, ranging from plot to farm and to the territorial scale (Moraine et al., 2017).

In this context, reconnecting livestock to specialized crop landscapes represents the addition of a trophic level in the planned biodiversity of agricultural systems (de Albuquerque Nunes et al., 2021). The grazing animal restores routes of nutrient cycling through forage ingestion and digestion, releasing, in the form of dung and urine, nutrients with greater lability (Arnuti et al., 2020) that impact soil stoichiometry. For example, P bioavailability in the soil increased 32% in grain crop areas where grazing was reintegrated (Deiss et al., 2016). By acting as "catalysts" of system processes (de Faccio Carvalho et al., 2009), grazing animals can both amplify ES provisioning with the application of best management practices or accelerate land degradation through the overexploitation of resources (e.g., overgrazing; **Figure 1**).

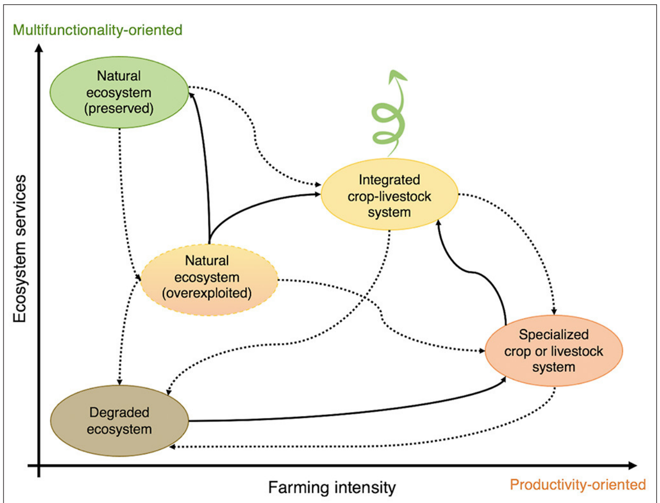

FIGURE 1 | Conceptual model of states and transitions in agroecosystems as a function of farming specialization and ecosystem services (ES) delivery. Solid and dotted lines denote positive and negative effects of the transition on ES delivery, respectively. Negative transitions could be caused by overexploitation of resources (e.g., overgrazing) or adoption of aggressive, non-conservationist agricultural practices (e.g., multi-pass tillage) or industrial livestock production (e.g., feedlots). Positive transitions could be promoted through sound grazing management practices (e.g., moderate grazing intensity), conservation agriculture practices (e.g., no-till and crop rotation diversity) and adoption of crop-livestock integration. Green arrow indicates that ES provided by integrated crop-livestock systems are potentially higher depending on synergisms levels (see explanation in the text). For clarity, only some possible states and transitions are shown.

While grazers are the dynamic agents driving changes in the landscape, plants react to grazing management (e.g., grazing intensity) by signaling the direction (+ or –) of these changes (e.g., herbage growth rates). The soil environment captures these impacts by acting as the "memory" of the system (de Faccio Carvalho et al., 2009). Thus, the reconnection of livestock in crop landscapes should be planned to explore the synergistic relationships between these components, rather than simply producing crops and animal products in the same unit area to improve farm income; "the whole should be greater than the sum of the parts" (FAO, 2010; de Faccio Carvalho et al., 2014). Then, those redesigned landscapes would approach their potential to enhance the provisioning of ES and rehabilitate landscape multifunctionality.

RECONNECTING LIVESTOCK AND CROPS ACROSS MULTIPLE SPATIO-TEMPORAL SCALES

Landscape multifunctionality depends not only on the reconnection of crop and livestock production but also on the distribution of these components over space and time. Ecosystem services are supplied by ecological functions associated with individuals, populations, and communities, and their spatio-temporal distribution is determined by the inherent scales in which these organisms operate (Laca, 2021). Because ES involve flows of matter, energy or information (Cadenasso et al., 2003), their production varies as a function of how these ES provisioning agents differ in mobility and perception of the environment, which is ultimately related to the organism size (Ritchie and Olff, 1999). As a consequence, ES responses vary with the spatio-temporal design on which the ICLS are implemented (Lindborg et al., 2017). Thus, a more complete and practical understanding of ICLS multifunctionality requires consideration of the spatio-temporal relations among the crop and livestock components.

Although some ICLS studies have predominantly focused on the succession of crops and pastures in the same paddock (Franzluebbers and Stuedemann, 2008; Acosta-Martínez et al., 2010; Assmann et al., 2014; Martins et al., 2017; de Albuquerque Nunes et al., 2021), crop-livestock integration can expand across various spatio-temporal scales. Importantly, though, only those designed to explore the synergistic relationships between the plant-animal-soil components of the system can be considered effectively integrated (FAO, 2010; de Faccio Carvalho et al., 2014). Examples of scenarios at different scales range from systems such as cover crop grazing in the understory of orchards (Ramos et al., 2011) and vineyards (Niles et al., 2017), where crop and livestock production are simultaneous in the same plot (i.e., closely integrated in space and time), to integration at the landscape or territorial scale (territorial crop-livestock integration; Moraine et al., 2017), where specialized crop and livestock farms coordinate exchanges of products or byproducts such as hay and manure (**Figure 2**). Certain models of integration can even involve more than one spatio-temporal scale simultaneously, such as happens in sheep-vineyard systems of California, where shepherds are contracted for temporary grazing to reduce weed competition and fuel load in the understory, among other benefits (Ryschawy et al., 2021). Although sheep and vineyards are closely integrated in space and time during the grazing period, a coordination of actions at the territorial scale is also required.

BENEFITS AND TRADE-OFFS OF RECONNECTING LIVESTOCK AND CROPS AT DIFFERENT SPATIO-TEMPORAL SCALES

The reconnection between grazing livestock and croplands has a fundamental role to play in system stoichiometry (Soussana and Lemaire, 2014). On the one hand, ruminants decouple C and N cycles, releasing digestible C through enteric emissions (3–5%), and returning mostly indigestible C via dung (60%) and high concentrations of digestible N in urine (70%) (IPCC, 2006). On the other hand, C and N cycles are recoupled by photosynthesis and plant growth processes until decomposition or grazing decouples them once again. Because the balance between C–N coupling by vegetation and C–N decoupling by animals determines the benefits and environmental impacts of ICLS, the distribution of livestock and crops over space and time can influence system dynamics in a positive or negative manner (Soussana and Lemaire, 2014). For example, when proper grazing management is applied (e.g., moderate grazing intensity), nutrient cycling is boosted by grazing of cover crops at the paddock scale without reducing the nutrient budgets.

For example, Alves et al. (2019) reported that P and K exportation from an ICLS area in sheep meat was 0.7 and 1.3 kg ha^{-1} yr^{-1} on average, respectively, over 14 years of annual soybean/maize - grazed Italian ryegrass succession, which represented only 6 and 5% of total exportations from that area (∼95% was exported in grain crops). Instead of being exported, the greatest share of nutrients is redistributed in the paddock during livestock foraging processes, affecting the spatial pattern of soil attributes and creating a mosaic of nutrient-rich zones near fences, supplement troughs and watering points, and nutrient-poor zones away from these attractants (Dubeux et al., 2006; da Silva et al., 2014, 2020). Alternatives to remedy the uneven nutrient distribution caused by grazing animals management practices such as variable location of supplement troughs and spatial patterns of seeding of preferred species. However, da Silva et al. (2014) and de Albuquerque Nunes et al. (2021) reported no differences in succeeding soybean yields (kg ha^{-1}) regardless of the spatio-temporal patterns of dung deposition caused by different grazing intensities in the preceding winter of a soybean-beef cattle system.

When the integration occurs at the landscape level, forage exportation (e.g., hay) from a hypothetical farm A to farm B will decrease nutrient availability in farm A if the same amount of nutrients is not replenished via, for example, manure application (which would ideally come from farm B). Also, nutrient excesses in farm B can drive leakage from the system if those nutrients are not managed properly or returned to farm A. Not returning nutrients to farm A characterizes a typical specialization trend, such as in intensive landless livestock farms in peri-urban regions of high-density population. This pattern of concentrating landless, specialized farms near urban areas to provide fresh feed by importing nutrients from outside is reported to result in concentration of nutrients and pollution when nutrients are not recycled properly (Chadwick et al., 2021).

Decreasing input dependence is a key factor in promoting sustainability (Bonaudo et al., 2014). There are numerous benefits of reconnecting grazing ruminants to croplands in these aspects. For example, the weed suppressing effect promoted by grazing best management practices in crop-pasture rotations combined with no-till management reduces herbicide dependence and associated costs of weed control at paddock scale (Schuster et al., 2016; Dominschek et al., 2021). There is also a reduction in the incidence of crop and livestock diseases in some cases. Roese et al. (2020) observed reduced incidence of diseases in the aerial parts of grain crops in ICLS with trees (eucalypts) due to the microclimate effect created in the understory. Portugal et al. (2018) reported a reduction in livestock diseases caused by ectoparasites (e.g., ticks) due to the break in the organisms' life cycle resulting from crop rotations. In both cases, there was a reduction in the use of chemicals as a consequence.

Through well-managed pastures there is an increase in the opportunity for visits by pollinators and other flying animals,

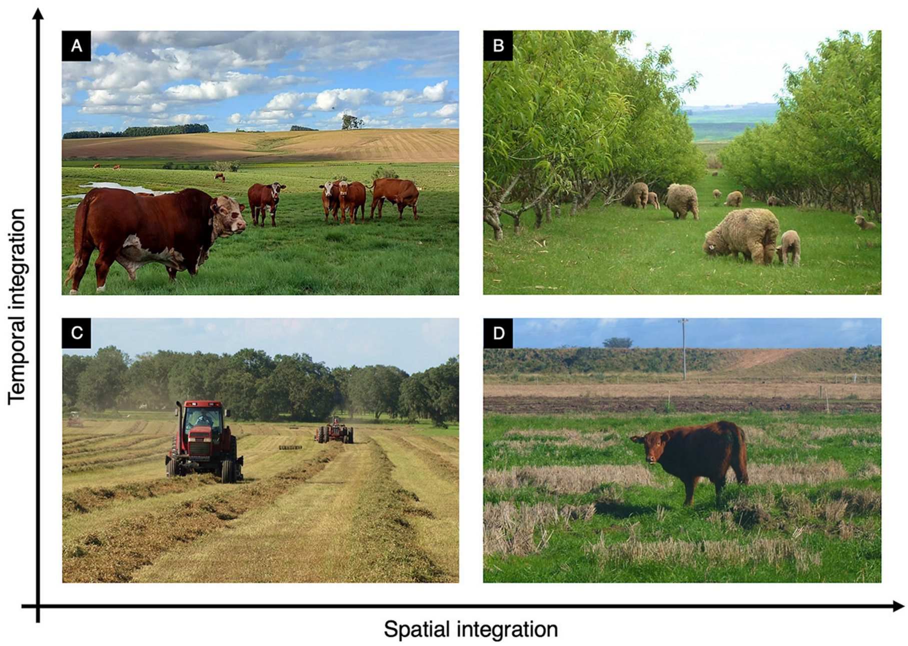

FIGURE 2 | Examples of integrated systems in multiple spatio-temporal designs. The axes denote the degree of interspersion in which crops and livestock are integrated along a spatio–temporal continuum. For a purpose of simplicity, only four discrete examples are shown, but multiple spatio-temporal designs are possible (see Bell and Moore, 2012). **(A)** Soybean cropping and native grasslands simultaneously occurring in neighboring fields. Pollination services for soybeans are enhanced because native grassland ecosystems provide habitat for a diversity of pollinators. Photo credit: Méia Albuquerque. **(B)** Sheep grazing the understory vegetation of a peach orchard. Grazing reduces the competitiveness of weed species and redistributes nutrients over the orchard. Photo credit: Thomaz Mercio. **(C)** Farmers harvesting hay. Integration at the landscape level involves coordinate exchanges of products or byproducts such as hay and manure between specialized crop and livestock farms. Photo credit: Marcelo Wallau. **(D)** Succession of crops and livestock in the same paddock, where stubble and cover crops are grazed by domestic herbivores, usually such as cattle and/or sheep. The picture shows a steer grazing in an Italian ryegrass pasture in winter following rice cultivation. Photo credit: Fernanda Moojen.

due to the heterogeneity promoted by grazing that creates new food webs (Orford et al., 2016; Van Rijn and Wäckers, 2016; Enri et al., 2017; Jacoboski et al., 2017). Pollination increases the production of seeds of forage species, decreasing the need to purchase seeds due to natural reseeding (Rao and Stephen, 2009; Boelt et al., 2015; Rundlöf et al., 2018). In addition, forest or pasture components create opportunities for shelter to predators of agricultural pests such as spiders and birds (Bretagnolle et al., 2011; Prevedello et al., 2018; Freiberg et al., 2020).

Reconnecting grazing ruminants to croplands promotes changes in the physico-chemical and biological control mechanisms in the soil and allows for an improvement in the efficiency of the use of nutrients by plants, resulting in a system less dependent on external inputs (Denardin et al., 2020). Resource-use efficiency per unit energy production was higher in soybean-Italian ryegrass rotations grazed by sheep compared to non-grazed Italian ryegrass cover crop at paddock scale (Farias et al., 2020).

Bell and Moore (2012) analyzed the multi-dimensional features of integrated livestock and crop enterprises according to space-time dimensions. Inspired by smallholder systems in western Africa and large-sized commercial farms in Australia, they proposed that benefits are higher when activities are closer to one another. The latter scenario is typical of Latin American integrated systems (de Faccio Carvalho et al., 2021), so we can use these closely integrated systems to explore the synergisms at their theoretical maximum level. Moreover, as mentioned earlier, the dichotomy of ungrazed vs. grazed cover crops being studied in Latin America provides a unique opportunity to examine the specific effects of the reintroduction of grazing animals in specialized crop landscapes in isolation from the plant effect (ungrazed pasture as a cover crop) and at smaller spatial scales (**Table 1**).

Assuming that the on-farm paddock scale represents the highest potential benefit to systems that reconnect livestock and crop production, it is worth noting how grazing animals are pivotal to restoring multifunctionality in specialized crop landscapes. By coupling and decoupling nutrients in the same area among different compartments, reconnected livestock-crop landscapes reach more complex organizational structures and increased hierarchical exchanges among the different living organisms. As presented in **Table 1**, multiple benefits cascade among different compartments affecting the whole system, whereupon emergent properties may arise (de Faccio Carvalho et al., 2018b).

At this point we surmise that system resilience is a key feature enhanced by reconnected crop-livestock landscapes that best represents the overall restoration of ecosystem

TABLE 1 | Grazer effect at the paddock level and at moderate grazing intensity on ecosystem service indicators.

Ecosystem service indicator	Grazer effect	References
Carbon stocks	Similar	Assmann et al., 2014
Food production	+ human-edible protein and energy	Martins et al., 2014 de Albuquerque Nunes et al., 2021
Methane emissions	+ enteric methane	de Souza Filho et al., 2019
Nutrient budgets	– Ca, Mg, P and K per unit food produced	Martins et al., 2014 Denardin et al., 2020 Alves et al., 2019
Nutrient cycling	+ N, P and K cycling (nutrient recycling)	Arnuti et al., 2020 Szymczak et al., 2020
Parasite suppression	– plant parasitic nematodes	Schmitt et al., 2021
Primary production (above and belowground)	+ total biomass production	Martins et al., 2017 de Albuquerque Nunes et al., 2019 Kunrath et al., 2020
Soil invertebrates (ground spiders)	+ abundance + species richness	Freiberg et al., 2020
Soil health (physical attributes)	+ soil aggregates + aggregate stability	de Souza et al., 2010b Conte et al., 2011
Soil microbiota	+ abundance + activity + diversity	Chávez et al., 2011 Wilson et al., 2018
System profitability	+ profitability	de Oliveira et al., 2013 de Albuquerque Nunes et al., 2021
System resilience	+ resilience – risk of financial loss	Szymczak et al., 2020
System stability	– variation in production – risk of production and financial loss	de Albuquerque Nunes et al., 2021
Weed suppression	– seed bank	Schuster et al., 2016

functioning. So, we can focus specifically on resilience-oriented integrated systems.

RESILIENCE: HARNESSING FUNCTIONAL DIVERSITY BY RECONNECTING LIVESTOCK TO CROP LANDSCAPES

Biodiversity is essential to building resilience (Ulanowicz et al., 2009) and can be characterized at two hierarchical levels of functionality that are important in regulating the structure and functioning of ecosystem services (Hooper et al., 2005; Duffy et al., 2007; Moonen and Bàrberi, 2008). The vertical dimension represents the trophic levels in the system, while the horizontal dimension is related to the number of species within each trophic level (Duffy et al., 2007). The vertical dimension of ICLS comprises plants and herbivores. On the other hand, the horizontal dimension is composed of functional genetic diversity, functional types of plants and ruminant and monogastric herbivores (Bell and Moore, 2012; Garrett et al., 2017). The design of reconnected crop-livestock systems provides a way of planning both dimensions of diversity in space and time, aiming to benefit from synergies between system components and achieve a higher overall system performance compared to the sum of individual performances (de Moraes et al., 2014; de Faccio Carvalho et al., 2018a).

ICLS are based on the philosophy of building resilience by increasing systems' capacity to adapt and self-organize in response to external disturbances, such as environmental changes (Bonaudo et al., 2014; de Moraes et al., 2014). This is largely due to the adoption of agricultural practices that increase soil organic matter, water and nutrient use efficiency, nutrient recycling, biodiversity, and spatio-temporal heterogeneity (Wezel et al., 2014; Altieri et al., 2015; Lemaire et al., 2015; Garrett et al., 2017; Van Oijen et al., 2020). To be resilient, an ecosystem must exhibit capacity to maintain its integrity over time and must have a reserve of flexible pathways, through a diversity of flows, to adapt to uncertainties (Ulanowicz et al., 2009; Altieri et al., 2015; Stark et al., 2018). From this perspective, Szymczak et al. (2020) observed that the greater diversity of nitrogen and phosphorus flows created by the reconnection between grazing animals and crop production in a commercial ICLS enhanced its resilience in comparison to a specialized soybean production system.

The vertical diversification represented by the addition of a trophic level when grazing herbivores are reconnected to crop landscapes increases the functional diversity and complexity of these systems (Duffy et al., 2007; Mori et al., 2013; Sanderson et al., 2013). It provides matter processing by digestion and nutrient cycling, as a small amount of the nutrients ingested by grazing animals is exported from the system. As a result of the improved nutrient flows and their ecological interactions (e.g., nutrient recycling via defecation; da Silva et al., 2014, 2020;

Arnuti et al., 2020), improvements in soil chemical, physical and biological attributes are observed at field scale (e.g., de Souza et al., 2010a,b; Chávez et al., 2011; Assmann et al., 2014; Martins et al., 2014; Deiss et al., 2016; Damian et al., 2021). Ultimately, it enhances the long-term stability of crop production without compromising grain yields (de Albuquerque Nunes et al., 2021). This rationale can also be applied on-farm (among paddocks) or at landscape scale (among farms). Animals would be moved at different periods and act as connecting agents between system components, improving agricultural resilience (de Faccio Carvalho et al., 2018a; Peterson et al., 2018; Stark et al., 2018; Paramesh et al., 2020; Tittonell, 2020).

In addition to the resilience of nutrient flows, the reconnection of grazing livestock to crop landscapes provides a means to enhance economic resilience by diversifying income, which buffers market and climate oscillations by smoothing farm incomes in poor crop production years (de Albuquerque Nunes et al., 2021). Therefore, when one production activity faces disturbances, the other activity may not be affected. Also, pasture-based livestock systems present greater adaptive capacity to deal with climatic oscillations, making ICLS less vulnerable than pure cropping systems. Using two differing approaches to study system responses to stress, both Szymczak et al. (2020) and de Albuquerque Nunes et al. (2021) observed a reduced risk of financial loss when crop and livestock production were reconnected (ICLS) relative to specialized soybean systems. Maximum profitability potential was increased by up to ∼30% in ICLS compared to the pure soybean system in the best environmental conditions (de Albuquerque Nunes et al., 2021).

The challenge of feeding a growing human population in a world of increasing uncertainties has been extensively debated by scientists. Therefore, to ensure food security, the foodscapes we plan today and into the future should consider the effects of climate change (e.g., increased weather variability and anomalies) and focus not only on increasing food production, but also approaches to deal with uncertainty. To this end, a study with historical data of a long-term experiment in southern Brazil (2001–2016) showed that reconnecting beef cattle to soybean systems increased the overall food production and long-term production stability in terms of human-edible protein. Moreover, it reduced the chance of failure in less favorable environments due to the production surplus provided by grazing cattle (de Albuquerque Nunes et al., 2021). Using the same historical ICLS dataset, Peterson et al. (2020) simulated climate conditions and the productivity and resilience of that ICLS for the next 40 years (2020–2060) using APSIM model, observing that ICLS gross margins exceeded that of the specialized system in 95% of years, while resilience to precipitation anomalies (more frequent in simulated climate scenario) depended on disturbance type and timing.

SOCIALSCAPES: MINDSET TRANSITION FROM SPECIALIZED TOWARD INTEGRATED SYSTEMS

Here we address part of the social dimension driving agricultural landscapes beyond the technical outcomes exposed throughout this paper. Reconnecting grazing animals to crop landscapes is not simply a technical decision. Because people ultimately manage landscapes, there are specific processes involving human behavior that are required to sensitize people and build the necessary conditions to manage more complex food production systems. First, there is an awareness step to prepare the mindset shift from current specialized production (thinking crop and livestock goals, planning and management separately) to a long-term, integrated systems thinking (Moojen, 2021). Second, the inherent complexity of ICLS implies the requirement of more complicated farm planning (i.e., spatio-temporal land use, financial planning, short- and long-term objectives). In this regard, proper advising is imperative to assist farmers in a desirable co-design processes (Moojen, 2021). Therefore, a distinct capacity building is crucial to both farmers and advisors, making them aware of the potential interactions between crops and livestock and capable of redesigning the farming system with ICLS principles by developing specific skills to manage multifunctional systems (Bonaudo et al., 2014).

It is worth mentioning that the specialization trend of crop and livestock production systems has side-effects beyond environmental boundaries. Academia, research and extension centers have been oriented toward segregated crop and livestock production. Consequently, teaching, research and extension initiatives focus on separate specialized outputs from each activity, and lack in the technical capabilities and knowledge adapted to ICLS (Garrett et al., 2020). Holistic approaches have been replaced by simple technical schedules. This state of affairs is a barrier to ICLS adoption (Bonaudo et al., 2014). To face it, the adaptation of agricultural courses to include systems thinking, didactic learning tools, and interdisciplinarity could help train future professionals to reacquire holistic perceptions and enable a path forward for sustainable ICLS implementation (Jouan et al., 2020).

Participatory methods for designing ICLS at the farm and landscape level have been reported as a promising way to connect farmers, advisors, and researchers to exchange knowledge and analyze scenarios (Ryschawy et al., 2014; Moraine et al., 2017). This is the case with "serious games," i.e., games aiming at specific learning outcomes (Wouters et al., 2009). Serious games can have goals such as (i) supporting negotiation of silvopastoral management (Etienne, 2003), (ii) assessing impacts of farming practices on sustainability (Jouan et al., 2020), (iii) designing technical and organizational scenarios among farmers (Ryschawy et al., 2018), (iv) exploring consequences of land-use decisions (Salvini et al., 2016) and co-designing spatio-temporal ICLS scenarios (Moojen, 2021). Overall, some tools and methodologies to assist people involved in the transitions are available, so it is necessary that their use be encouraged and customized to each context to remove barriers to multifunctional landscape design.

At the institutional scale, robust extension systems are needed to transition toward ICLS. Governmental projects must consider the greater complexity of ICLS in relation to specialized systems, thus providing flexibility for adapting tools and approaches for each farming context and skills like leadership and systemic vision to those involved in the project (Price et al., 2009).

Equally as important as the sensitization and empowerment of the people in the system is the economic viability of ICLS, which is crucial for adoption at the farm and landscape level. Credit availability for ICLS projects, supply chain infrastructure, and farmers' willingness to diversify production are some of the factors determining ICLS adoption (Gil et al., 2016). As mentioned in previous sections, studies have shown the importance of livestock production as an effective way for diversifying revenue sources in specialized agricultural systems, increasing overall system productivity, profitability, and stability to external stressors, and consequently reducing economic risks (Bell and Moore, 2012; de Oliveira et al., 2013; Szymczak et al., 2020; de Albuquerque Nunes et al., 2021). However, each ICLS has its own idiosyncrasies. For example, when a forest component is involved, economic benefits need to be analyzed on a larger temporal scale given the time needed for woodcuts, harvesting of fruit, or even shade for livestock comfort. The challenge, therefore, is to quantify and plan economic flows both in the short- and in the long-term according to each ICLS farm design.

CONCLUSIONS

In this manuscript we present evidence that the reconnection of grazing livestock to specialized crop landscapes can restore biogeochemical cycles decoupled by uniform landscapes lacking the diversity necessary for proper ecosystem functioning. Our approach enables disentangling the effects of forage plants from the grazing animal to underline ecosystem service indicators promoted specifically by the grazing process. This perspective highlights the capacity of grazing animals to recover landscape multifunctionality. Spatio-temporal designs of crop-livestock integration will affect the level of ecosystem services delivered. Multiple benefits can cascade over the whole system if moderate grazing is adopted, and resilience is a key feature that arises. This path of mixing crops and livestock embraces complexity against current specialization trends, requiring capacity building and mindset shifting. To conclude, grazing animals have an important role in the design of future foodscapes. Grazing herbivores are part of natural ecosystems, and commercial landscapes should aspire to mimic the beneficial functions of natural ecosystems.

AUTHOR CONTRIBUTIONS

PF and GL conceived the initial idea. PF, PA, and AP-P wrote the first draft. PF, PA, AP-P, LS, WS, and FM provided input to the original draft. PF, PA, AP-P, LS, WS, FM, and GL revised the final version. All authors contributed to the article and approved the submitted version.

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Beyond CO_2: Multiple Ecosystem Services From Ecologically Intensive Grazing Landscapes of South America

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Sustainability assessments to inform the design of multifunctional grazing landscapes need to look beyond greenhouse gas emissions to simultaneously embrace other social and environmental criteria. Here I briefly examine trade-offs and synergies between the productivity of graze-based livestock systems and the environment, and share a few generic guidelines to design pathways for the ecological intensification of livestock systems following agroecological principles. I draw from experience on livestock farming in the *Rio de la Plata* Grassland Biome of South America (Argentina, Uruguay, and Brazil). Livestock systems based on native grasslands in this region may have greater carbon footprints (13–29 kg CO_2 eq. kg LW^{-1}) than intensive grass-feedlot systems in the region (9–14 kg CO_2 eq. kg LW^{-1}) or the average range reported for OECD countries (c. 10–20 kg CO_2 eq. kg LW^{-1}) when calculated per unit product, but only 20% greater when expressed on an area basis. Yet they use less external energy (10x) or nitrogen inputs (5x) per kg live weight (LW) produced, provide ecosystem services of local and global importance, such as carbon storage, habitat protection for biodiversity, watershed regulation, clean water, food and textiles, livelihoods and local cultures, and provide better living conditions for grazing animals. Traditional graze-based systems are less economically attractive than intensive livestock or grain production and they are being replaced by such activities, with negative social and environmental consequences. An ecological intensification (EI) of graze-based livestock systems is urgently needed to ensure economic profits while minimising social-ecological trade-offs on multifunctional landscapes. Examples of such EI systems exist in the region that exhibit synergies between economic and environmental goals, but a broad and lasting transition towards sustainable multifunctional landscapes based on agroecological principles requires (co-)innovation at both technical and institutional levels.

Keywords: agroecology, sustainability, livestock, trade-offs, environment, carbon footprint

INTRODUCTION

Discourses on global issues such as climate change, diet-related human health, deforestation, desertification, air and water pollution or biodiversity loss point to livestock production as one of their main causes (e.g., Opio et al., 2013; Herrero et al., 2015; FAO, 2018). Admittedly, simplified industrial livestock systems rely heavily on external inputs (feeds, fertilisers, pesticides), antibiotics, growth promotors, fossil fuels, etc., are vulnerable to diseases, to climatic variability, to price spikes, etc., host little biodiversity, impact negatively on the environment, compromise animal welfare, do not provide substantial amounts of rural jobs, often need governmental subsidies to be economically viable, and tend to generate ecosystem disservices more frequent than services. They require a profound redesign to become sustainable. Traditional livestock production systems based on native grasslands and woodlands, on the other hand, often provide ecosystem services that may compensate for the environmental damage that they cause (cf. Tittonell et al., 2020). Yet these systems are under threat do to their poor ability to compete with more profitable land uses, to institutional pressure to undergo intensification or "modernisation," or to the ageing of traditional livestock keepers associated with the migration of the rural youth to urban areas (e.g., Novotny et al., 2020; Solano-Hernandez et al., 2020). An intensification based on agroecological principles is urgently needed in both industrial and traditional livestock systems to arrive at a third way strategy by which economic, social and environmental trade-offs are minimised, resulting in multifunctional, sustainable grazing landscapes.

An important element – but not the only one – that prevents the development and implementation of knowledge, technologies and institutional incentives to support a transition towards multifunctional grazing landscapes is a poorly informed debate around livestock environmental sustainability. Quantitative assessments of environmental impacts of livestock systems have focused chiefly on carbon footprints (e.g., Opio et al., 2013; Becoa et al., 2014), and less frequently on other aspects such as biodiversity, energy and nutrient efficiencies, watershed regulation or socio-cultural values. The use of simplifying environmental accounting methods, such as the life cycle assessment, has often led to conclude that intensive livestock systems such as feedlots or animal warehouses are more "sustainable" than grazing systems due to their lower CO_2 emission rate per kg of produce (e.g., De Vries and De Boer, 2010). This is certainly a narrow view on what sustainability really means. But such understandings are also fuelled by the fact that the current ability and potential of grazing systems to provide ecosystem services of local and global importance, and the trade-offs with their environmental impacts, have been generally poorly studied (FAO, 2019). And even less frequent are studies that simultaneously assess the various economic, social and environmental performances of alternative livestock systems, or that document comprehensive processes of system redesign and transition. Sustainability assessments to inform the design of multifunctional grazing landscapes need to look beyond greenhouse gas emissions to simultaneously embrace other social and environmental criteria.

The ultimate goal are multifunctional landscapes on naturally heterogeneous grazing ecosystems, that foster ecosystem services (provision, support, regulation, and cultural) and minimise trade-offs with other environmental indicators, such as the carbon foot print. Here I briefly examine trade-offs and synergies between the productivity of graze-based livestock systems and environmental indicators associated with the UN Sustainable Development Goals (SDG). For conciseness, I present quantitative examples that do not deal directly with socio-cultural ecosystem services except marginally with revenue, as the goal of this paper is to expand the debate from CO_2 to other environmental sustainability criteria. Then, I share a few guidelines that may contribute to designing pathways for the ecological intensification of livestock systems following agroecological principles, in order to overcome such trade-offs. I draw these ideas from ca. 20 years of experience in research – hence the frequent self-citation – and implementation of ecologically intensive farming in the *Rio de la Plata* Grassland Biome of South America, engaging with farmers and researchers in trajectories of learning and development. I conclude with a few generalizable messages that can inform and hopefully inspire the design of multifunctional grazing landscapes.

TRADE-OFFS BETWEEN PRODUCTIVITY AND THE ENVIRONMENT

Trade-offs around livestock production are often presented as an "either-or" choice between consuming animal products vs. cooling the planet. Vegetarian diets and veganism are advocated as the solution to our environmental problems, especially global warming. One problem with this approach is that it neglects the various functions and services associated with livestock, from ecological to social and cultural (e.g., Hoffmann et al., 2014). This is particularly true for grazing livestock systems, which next to providing food and incomes contribute to nutrient cycling and circular farming, to protect habitats for biodiversity, to regulate water and carbon flows in ecosystems, to preserve traditional livelihoods and their cultural capital, and to transform inedible plant biomass into valuable food for humans. Yet, these are not arguments in favour of increasing meat consumption or that of any other animal product. Meat consumption needs to be re-dimensioned at global scale, drastically reduced, but also better distributed across regions (for example, recommended *per capita* meat consumption rates are in the order of 26 Kg year^{-1}; yet current world average is 43 Kg year^{-1}, average consumption in the US or Australia is above 120 Kg year^{-1}, around 80 in the UK and western Europe, 48 Kg year^{-1} in China, from 10 to 20 Kg year^{-1} in Africa, and $<$5 Kg year^{-1} in India).

Grazing livestock may play a positive role in agroecosystems. Virtuous crop-livestock interactions are central to the design of sustainable landscapes through agroecology (e.g., Bonaudo et al., 2014). Unfortunately, the trade-offs and synergies between grazing livestock production and other ecosystem services have been poorly documented, at least in quantitative terms. Such is the case also for the sheep and cattle ranging systems in the *Río de la Plata* grasslands (RPG), which comprises vast areas of Argentina, Uruguay, and Brazil. These nearly 700,000 km^2 of native grasslands and woodlands store more than 5% of the soil carbon of the continent, prevent soil erosion, and provide clean water to major cities in the region where up to 20 million people live, host respectively 800 and 200 endemic species of grasses and legumes, a wide diversity of bird and mammal species, host 65 million livestock heads and sustain the livelihood of c. 430,000 local family farmers. These traditional systems are however under threat due to the expansion of more profitable activities that produce for the export market (soya, maize, rice), thereby displacing family farmers and converting land from grasslands and woodlands into uniform monocultures with high environmental impact (Modernel et al., 2016). Narratives that associate traditional grazing livestock with global warming do not contribute to halt such a trend.

Graze-based livestock systems in this part of the world encompass a diversity of management systems that range from full cycle cattle (calving, backgrounding and finishing on the same farm) to more specialised cow-calf or finishing/fattening systems. Traditional family farms are more often associated with cow-calf/sheep rearing, generally on unfertilized native grasslands, whereas specialised fattening systems tend to be more entrepreneurial and rely on intensive feeding regimes (Ruggia et al., 2015). Options for intensification of meat production are often oriented towards increasing the efficiency of the later stages in the production cycle, those concerned with the backgrounding and finishing phases. The various phases of the production cycle may take place with the animals grazing on native grasslands or on sown pastures (or leys, often involving the use of fertilisers, soil correctors and sometimes irrigation), or confined in feedlots where they are fed cereals (Modernel et al., 2016). Picasso et al. (2018) analysed the productivity and environmental performance of systems varying in their intensity during backgrounding and finishing, from those that relied exclusively on native grasslands (Grass-Grass), to those that combined them with sown pastures (Grass-Past), that relied exclusively on sown pastures (Past-Past), or that fed concentrates during the finishing phase (Past-Feed) (**Figure 1**). Emission calculations were done using IPCC 2006 tier 2 equations, as described in Modernel et al. (2013), considering also the emissions associated with production and distribution of feeds and other inputs (fertilisers, seeds, herbicides). Soil carbon was assumed to remain constant, as recommended by the IPCC. When comparing the four systems, beef productivity increased respectively from 140 to 300 kg LW ha^{-1} (109% increase), whereas the carbon footprint measured in CO_2 equivalents per kg LW consequently decreased by 59% in the same range as the systems became more productive – a dilution effect!

Dilution effects that result from expressing CO_2 emission rates per kg of live weight (LW) are an artefact of the carbon footprint calculation and often used to portrait intensive livestock systems such as feedlots as being more sustainable than graze-based systems (e.g., McGinn et al., 2008; Capper, 2010). There are several reasons to explain this pattern. A cereal grain diet fed to cattle bypasses rumination and hence CH_4 emissions are lower per kg of dry mater taken in by the animals. In addition, feedlot animals live generally shorter, they gain weight faster at the expense of their health (e.g., acidosis is common among grain-fed young steers), become "roundish" much earlier than grazing

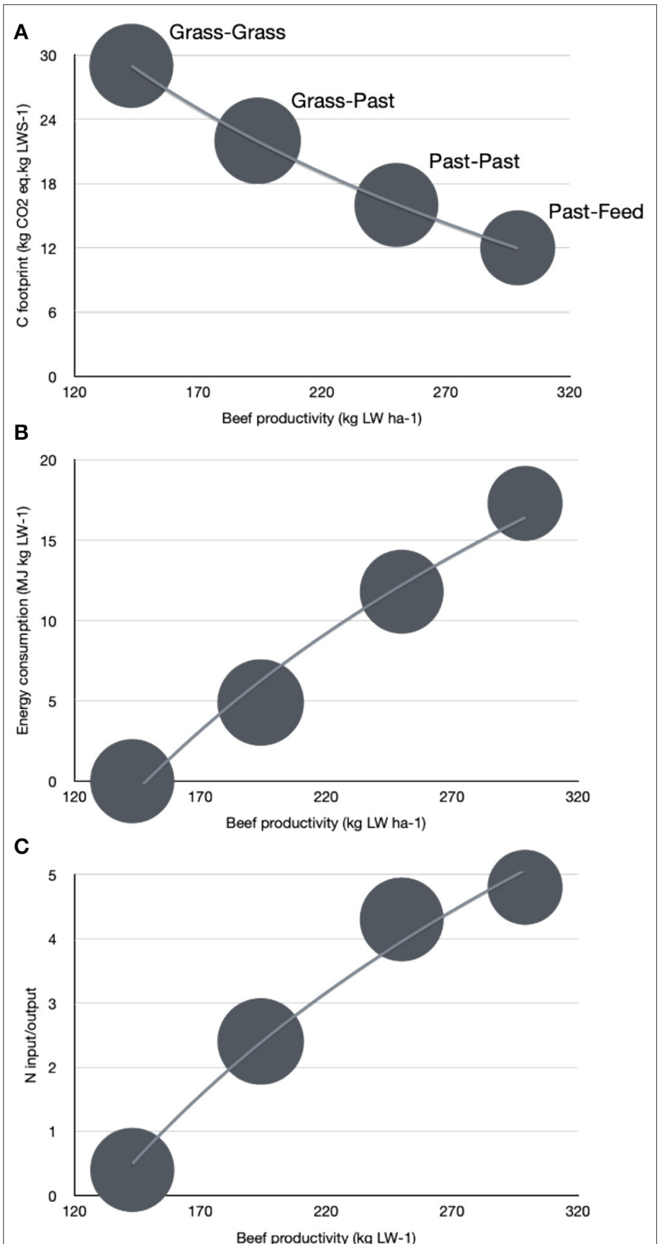

FIGURE 1 | Calculations of environmental footprints of four representative beef production system types in Uruguay varying in their intensity during the backgrounding and finishing phases, using native grasslands (Grass), sown pastures (Past), or feedlots (Feed). Carbon footprint **(A)**, energy consumption **(B)**, and nitrogen inputs **(C)** are plotted against average beef productivity per hectare per year. The size of the circles represents the average CO_2 emission rate per hectare per year. Grass-Grass indicates that both the backgrounding and finishing phases are done on native grasslands, Grass-Past indicates backgrounding on grasslands and finishing on pastures, and so on. The graphs were drawn using calculations presented by Picasso et al. (2018).

animals and are consequently slaughtered at a younger age, spending no more than 4 months on average in a feedlot. Since emission rates are calculated over the entire life span of an animal, shorter life spans have an additional dilution effect on the average emission rate per unit LW. When expressing emission rates per unit land instead of LW, systems that background and finish cattle exclusively on native grasslands without external inputs emitted on average 4,095 CO_2 eq. ha^{-1}, those that finished on pastures 4,330 CO_2 eq. ha^{-1}, those that used exclusively pastures 4,071 CO_2 eq. ha^{-1}, and those that finished in a feedlot 3,250 CO_2 eq. ha^{-1} (emissions per unit land are represented by the size of the circles in **Figure 1A**). Thus, when the carbon footprint is calculated on an area basis – which makes perfect sense for a footprint – intensive beef production systems emit c. 20% less CO_2 equivalents than traditional grazing systems on native grasslands, or than intensive grazing systems on sown pastures.

Fossil fuel energy consumption per kg LW produced, which is another environmental indicator associated with global warming, shows however critical increases as systems intensify in this way (**Figure 1B**). And, although more intensive livestock systems are also often portrayed as being more efficient in the use of external resources, the calculations of Picasso et al. (2018) show that the nitrogen input to output ratio becomes increasingly unfavourable as systems intensify relying increasingly on sown pastures and feedlots (**Figure 1C**). Intensive pasture and feedlot systems need five times more N than fully grazing systems per kg N exported as output. Yet although the average values for all these indicators fluctuates substantially between fully grazing to grazing plus feedlot systems (cf. **Figure 1**), they are still far from average values reported for intensive livestock systems worldwide. For example, Modernel et al. (2018) showed that beef systems in OECD countries are 52% more productive and emit 35% less (per unit LW!), but they use 500% more fossil fuel energy as compared with traditional grazing systems in the *Rio de la Plata* region.

But beyond these popular indicators to assess livestock sustainability, there are other impacts of intensification to be considered, which are beyond the scope of this paper, for example: Concentration of nutrient-rich dejections and more frequent use of pharmacological ingredients leads also to water pollution in the surrounding of feedlots with negative effect for human populations (e.g., Elorriaga et al., 2013). When the manure from such intensive operations is used to amend soils in fresh vegetable production there are high risks of contamination and antibiotic resistance building (Jechalke et al., 2014). Further, converting native grasslands and woodlands into fertilised pastures sown to exotic species such as ryegrass, or into annual cropping fields to produce the necessary feed grain, has also enormous consequences for soil, water and biodiversity conservation. Effects of land conversion and grazing management on biodiversity range from losses in abundance and richness of soil organisms (e.g., El Mujtar et al., 2019) or plant species diversity (e.g., Lezama et al., 2013; Pizzio et al., 2016; Herrero-Jáuregy and Oesterheld, 2018) to negative effects on amphibians, birds and mammals (e.g., Alkemade et al., 2013; Dias et al., 2014; Azpiroz and Blake, 2016; Schieltz and Rubenstein, 2016). Shifting from direct grazing to frequent mowing under intensive cut-and-carry feeding systems has also serious consequences for biodiversity, especially for ground nesting birds or the arthropods and worms they feed on (Kentie et al., 2016). Beyond global assessments on the effect of grazing management on soil carbon sequestration (e.g., Tanentzap and Coomes, 2012; Abdalla et al., 2018), studies in the *Rio de la Plata* region indicate that switching from native vegetation to sown pastures reduces soil carbon storage by more than 60% (Piñeiro et al., 2010), and water infiltration by almost 100% seriously affecting watershed regulation (floods, aquifer recharge) and soil erosion (e.g., Nosetto et al., 2012). Soils of native grasslands managed with high forage allowance (adjusted stocking rates over time-space) allow fast, resilient recovery of forage productivity after severe droughts (Modernel et al., 2019).

Next to biodiversity and the environment, animal welfare is also critically compromised as animals move from year-round grazing at sparse stocking rates on native vegetation to being stalled at high densities in a feedlot, where they receive antibiotics as growth promotors, have no access to grazing, stand on muddy soil and suffer confinement-related stress (e.g., Nielsen and Zhao, 2012; More et al., 2017). In **Figure 2**, un-managed livestock harvesting represents old traditional systems that have now virtually disappeared from the *Rio de la Plata* region, in which livestock were set free and gathered every year to "harvest" animals to be sold on the market (the system persists in part of the Patagonia or Andean drylands). This sort of natural welfare is not necessarily optimal for domestic animals, which require for example reproductive assistance, veterinary care, etc. Maximum welfare is achieved when animals are provided these plus also shelter, protection from predation, supplementary feed in times of drought or snow, clean and easily accessible water, organised mating and weaning around forage availability, etc. Productivity increases as animal welfare increases. Beyond a certain point, however, animal welfare is increasingly compromised in favour of livestock productivity, to the extreme of reducing it beyond cruelty levels when ruminants spend most of their life in a feedlot feeding on concentrates. Traditional yet stereotyped systems in the *Rio de la Plata* Grassland Biome are represented in **Figure 2** by the range between points a, family systems, and b, entrepreneurial graze-based systems relying largely also on native grasslands. **Figure 2** also indicates the scope for designing ecologically intensive grazing landscapes (see Towards Ecological Intensification: Design, Co-innovation, and System Transition section), represented by the green dashed line, which must aim to increase productivity while maintaining socially acceptable levels of animal welfare.

TOWARDS ECOLOGICAL INTENSIFICATION: DESIGN, CO-INNOVATION, AND SYSTEM TRANSITION

In spite of the array of services they provide, from conservation of biodiversity or landscape regulating functions, to lifestyles and cultures, traditional grazing livestock systems are disappearing as being outcompeted by more profitable farming activities. Curtailing this trend requires measures to increase the

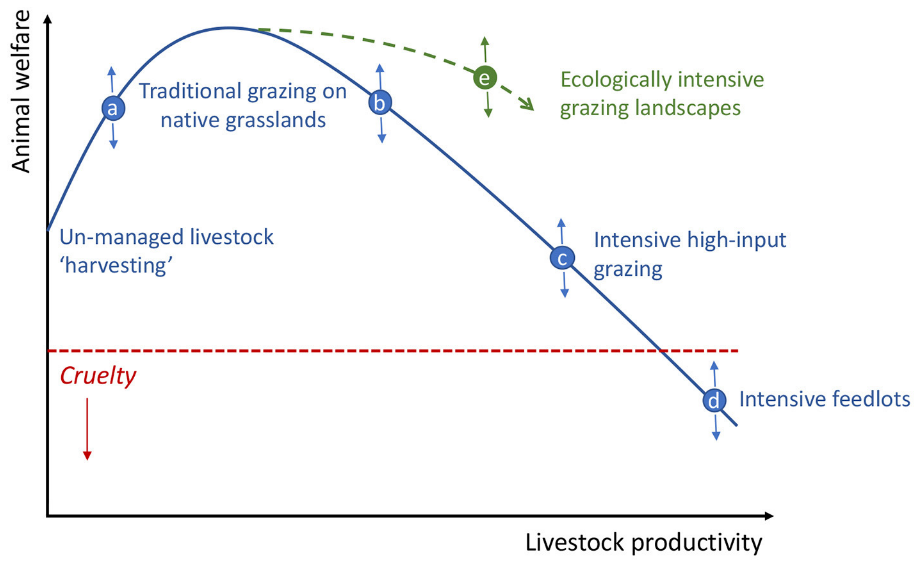

FIGURE 2 | A representation of the relationship between (perceived) animal welfare and livestock productivity following the conceptual mode of McInerney (2004) to depict the various beef production systems that can be found in the *Rio de la Plata* Grassland Biome. Red dotted line represents a minimum welfare level below which we may speak of cruelty towards domestic animals. Points a and b indicate respectively the approximate situation of traditional family and entrepreneurial graze-based livestock systems in the region. Vertical arrows indicate variation in terms of animal welfare within each type of system. The green dashed line represents the scope of ecologically intensive razing landscapes in terms of increasing productivity while minimising the trade-offs with animal welfare.

profitability of family livestock keepers in the region. The ecological intensification of traditional grassland-based livestock systems has been proposed as a way to increase productivity while reducing costs and maintaining the provision of key ecosystem services (Albicette et al., 2017). But, what is ecological intensification? What is an ecologically intensive grazing landscape?

Definition and Design Principles

Ecological intensification relies on the knowledge and design principles of agroecology (cf. Tittonell, 2014). There are several definitions and interpretations of the term "intensification" and its qualifiers, but here I use the one adopted in Latin America by the PROCISUR (*Programa Cooperativo para el Desarrollo Tecnológico Agroalimentario y Agroindustrial del Cono Sur*: www.procisur.org.uy) in 2019: "Ecological intensification is a process of gradual improvement of the ecological efficiency of production systems through technological and institutional innovation, with the aim of using the natural functionalities offered by ecosystems to promote higher productivity with less environmental impact, maintain or improve the natural resource base, reduce dependence on non-renewable resources and favour adaptability, resilience and social equity" (Tittonell, 2018). This generic definition needs to be made specific for livestock systems, and in particular for grazing systems, i.e., their biophysical characteristics, socioeconomic context, management and business model, history and long-term strategy. Yet, I find it useful to derive a few general principles for the design of ecologically intensive landscapes. These principles are intended to be applicable regardless of the type of production system in question, and can be outlined as Tittonell (2020b):

1. **Match**: match the supply of resources with the requirements and demands of the production system (plant- or animal-based);
2. **Fine-tune**: regulate or correct those factors that impede or reduce the efficiency of the relationship between environmental supply and the system's requirements;
3. **Reduce**: reduce the dependence of the system on external inputs, particularly those obtained from non-renewable resources or that cause direct environmental impact;
4. **Sustain**: sustain the natural resource base and associated ecosystem services over time and increase the resilience of the system against exogenous disturbances.

These guidelines are subject to the objective(s) for which the landscape is designed or managed. Objectives may include production, conservation, regeneration or reproduction of natural capital or the productive resource base, provision of ecosystem services of local or global importance, diversification, investment, etc., or be of a cultural, ethical or affective nature. Hence there is not a single set of practises that could be universally applied to engage in an ecological intensification trajectory, as they will be objective- and context-specific. **Table 1** offers however some examples of possible practises simply as illustration.

Examples of ecologically intensive management in practise were documented in the *Rio de la Plata* Grassland Biome by Modernel et al. (2018), who identified, through a combination of Pareto ranking and archetype analysis of graze-based

TABLE 1 | Four steps proposed for the ecological intensification of grazing livestock systems and examples of possible management practises.

Steps in ecological intensification	Description	Possible practises
Matching	Match resources (radiation, water, nutrients, biomass) with crop or animal requirements, over time (season) and landscape units	Selection of adapted species and landraces, match grassland productivity to demands of different categories of livestock, or mixes of species
Fine tuning	Correct for or regulate mismatches (weed, pest and disease regulation, water, nutrient and C flows)	Herd measures to categorise requirements (e.g., weaning, backgrounding); management of parasite cycles in animal-grassland continuum
Reducing	Reduce dependence on external inputs, particularly of non-renewable resources through harnessing ecosystem services of support and regulation	Integrated management of animal health (i.e., One health approach) to reduce antibiotics; N fixation in pastures to reduce fertiliser N inputs; cultivation of protein rich fodder as feed
Sustaining	Build resilience mechanisms to face shocks and stresses, and adaptation capacity, long-term maintenance or improvement of the natural capital and ecosystem services	Maintenance of vegetation structure, resting periods and exclosures, re-seeding periods; avoid soil compaction, overgrazing, erosion, nutrient hotspots; bring genetic diversity in the herd(s)

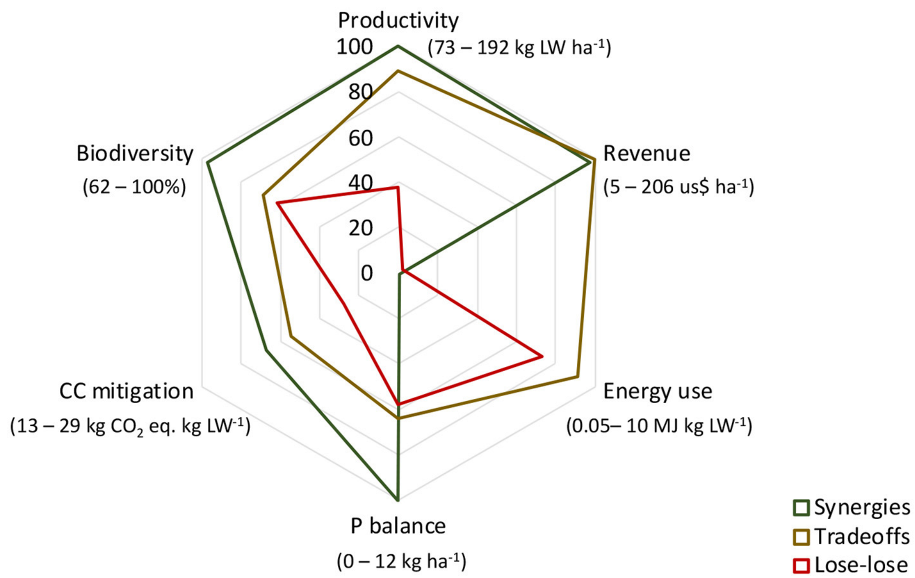

FIGURE 3 | Economic and environmental performance of archetypal grazed-based livestock farms in Uruguay, *Rio de la Plata* Grassland Biome, derived from a survey of 280 cases by Modernel et al. (2018). The archetype analysis was based on a Pareto ranking of the sampled farms with respect to the various indicators (plus N balances, not shown in this graph). Four archetypes were found that represented win-win (synergies), win-lose (trade-offs), lose-win, and lose-lose situations in terms of these economic and environmental indicators, using local expert knowledge for benchmarking. Lose-win situations are not represented in this graph, as viable economic performances are a non-negotiable requisite to local stakeholders. Only 41 farms fitted these four archetypes of which only five farms stood out as win-win cases. Values between brackets indicate the range of average values for each archetype (min-max). Graphics built with data presented by Modernel et al. (2018).

livestock farms in Uruguay (n = 208), those that stood out in terms of economic and environmental performances ("Synergies" in **Figure 3**). The authors also identified archetype farms that exhibited good economic performance but less favourable environmental indicators ("Tradeoffs" in **Figure 3**), good environmental but poor economic performance (not shown in **Figure 3**), and poor performance on both criteria ("Lose-lose" in **Figure 3**). Beyond the implications of the absolute or comparative values of some of these indicators, this study revealed the existence of practical examples of ecologically intensive livestock farms in the region, positive deviants that can be used a benchmarks for learning and innovation, or to inform policy making (*NB*: P balances in **Figure 3** are plotted in the opposite sense as compared with the original publication, since I consider P mining to be an acuter problem than P accumulation in the soils of the region). The experience in the *Rio de la Plata* region indicates that the ecological intensification of livestock on native vegetation, particularly the matching step proposed here, requires spatially explicit management of the heterogeneity of the grassland ecosystem (e.g., Soca et al., 2013; Trindade et al., 2016; Do Carmo et al., 2019). This, and the fact that sustainable landscapes are expected to be multifunctional, is why I prefer

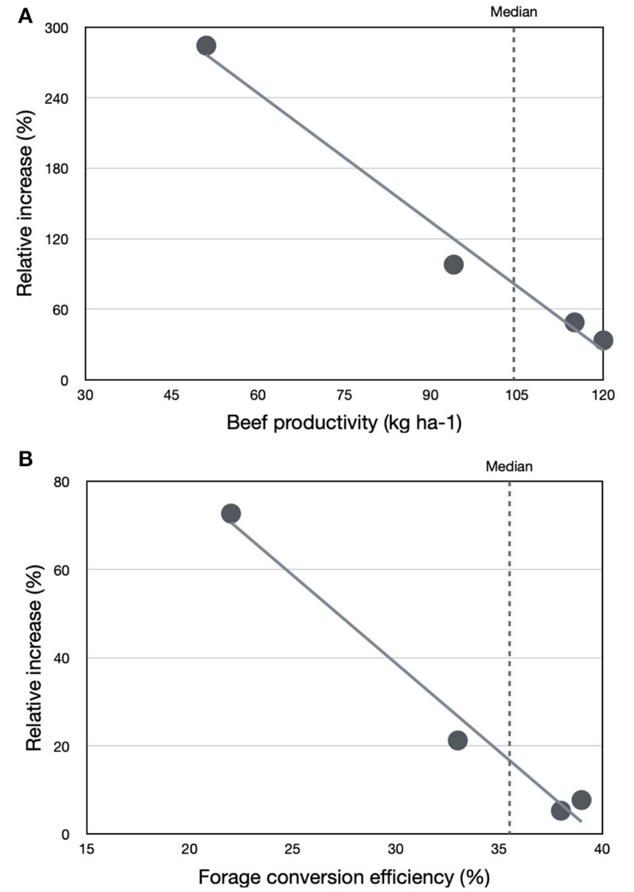

FIGURE 4 | Room for improvement in terms of beef productivity **(A)** and forage conversion efficiency **(B)** when farmers engaged in regional innovation platforms, based on a 1998-2010 study at municipal level in General Lamadrid County, Buenos Aires, Argentina (*Rio de la Plata* Grassland Biome), using data from Pacín and Oesterheld (2015). Lamadrid County comprises 481,000 ha and had 437,000 heads of cattle at the time of this study, of which 37,000 were owned by farmers who participated in platforms. The four points shown in the figures correspond to years 2000/1, 2003/4, 2006/7, and 2009/10. Y-axis depicts the relative difference (%) between farms with and without technical assistance.

to speak of ecologically intensive grazing landscapes, and not just grazing systems. The term landscape includes not only the spatial but also the social, ecological and cultural aspects of the grazing system.

Innovation Systems

The ecological intensification of graze-based livestock systems is highly knowledge intensive. Approaches that combine different types of knowledge through co-innovation processes are most successful at fostering ecological intensification (Tittonell et al., 2016). Since 2007, Rossing et al. (2021) crafted co-innovation as an approach for governance and management of ecological intensification processes, combining three elements: a complex adaptive systems perspective, social learning settings, and dynamic monitoring and evaluation. The experience collected so far shows that the combination of external technical assistance, co-construction of knowledge, and adapted process technologies are central to ecological intensification processes. **Figure 4A** illustrates the gains in livestock productivity that were achieved in General Lamadrid County, Argentina (*Rio de la Plata* Grassland Biome) during the period 1998–2010 by farmers who engaged in co-innovation platforms consisting of regional farmer networks (Pacín and Oesterheld, 2015). The lower the average productivity of the farms the greater the gains that were realised, of up to 300% greater beef productivity in some cases. Although access to knowledge-sharing platforms had a positive impact on forage productivity (ca. 30% increase on average – data not shown), the greatest part of the gain in beef productivity was explained by an increase in forage conversion rates (**Figure 4B**), which is a sensitive management-related indicator. Access to knowledge in this case was achieved through farmers' participation in regional innovation platforms known as Regional Consortiums for Agricultural Experimentation (CREA: www.crea.org.ar), a private network created in 1957, and a long-standing example of co-innovation in practise.

Agroecological Transition

The few examples presented here illustrate that there is room to improve the performance of grazing livestock systems, minimising production-environment trade-offs through design and management, to preserve biodiversity and propend to multifunctional landscapes. The ecological intensification of grazing landscapes is a special case of what is generally known as agroecological transition, or the necessary social-ecological reconfiguration of agroecosystems to produce following agroecological principles (Tittonell, 2020a). Agroecological transitions have been described in different ways but most definitions make implicit use of the Efficiency-Substitution-Redesign concept, which was probably coined by Hill and MacRae (1995) as the ESR-model, but frequently used by classical authors in agroecology such as Gliessman (2006). There is a narrow relationship between the phases of an agroecological transition and the various domains at which innovation is needed, such as technical and institutional innovation (cf. Tittonell, 2014). I try to explore this idea further with the diagrams of **Figure 4**, which represent (A) the domains for innovation as nested sets of constraints, and (B) the phases of an agroecological transitions following the ESR-model plus a governance phase. *NB*: None of these processes is linear or sequential! The use of "phases" is just the simplest way to explain it.

There are substantial gains to be achieved in both economic and environmental ecosystem services through proper management practises (e.g., **Figures 3**, **4**), particularly considering heterogeneity management in patio-temporally diverse grazing landscapes. Adaptive, well-informed and spatially explicit management is a requisite to improve systems efficiencies (**Figure 5**). But this is not enough for ecological intensification. The ability of management practises to stir change towards sustainable, multi-functional landscapes is often constrained by the availability of the necessary technologies to sustain agroecologically intensive management. This is represented by the red set in **Figure 5** (Technology constraints). Beyond

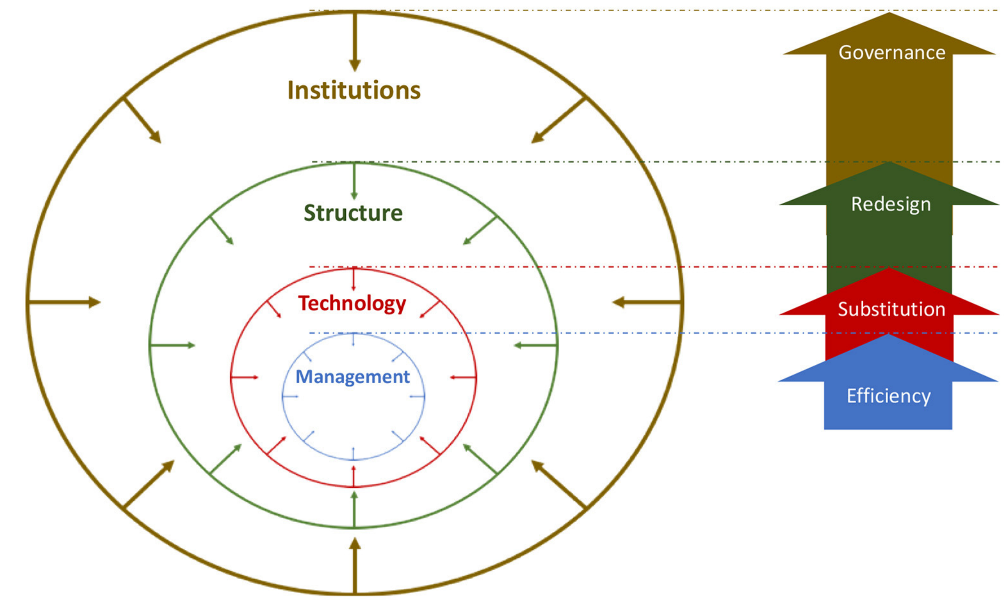

FIGURE 5 | Innovation domains for the ecological intensification of livestock systems in multi-functional landscapes represented as sets of nested constraints (left), and four phases in agroecological transitions necessary to face the constraints imposed by each domain (right). The size of the sets and the length of the block arrows indicate the relative strength of the constraints to agroecological transitions.

technologies to support spatially explicit, precise management of heterogenous grazing landscapes, which are developing fast, there is a major gap in the realm of input technologies that constrains agroecological livestock intensification. For example, and although progress is underway, the design of biological solutions to replace traditional antibiotics or vermifuge treatments has still much ground to cover. Yet, even when bio-based technologies would be available for a complete input substitution, sustainable multifunctional management may be hampered by structural constraints in the production system that would require a thorough redesign. For example, systems that rely on single species of plants and animals, deployed over homogeneous landscapes (e.g., dairy cow-perennial ryegrass type of systems), offer narrow space for manoeuvring in terms of ecological intensification. These systems depend on inputs, whether synthetic of biological, because they are ecologically out of balance. As vastly discussed here, simplified industrial livestock systems would often require profound redesign measures to become sustainable (i.e., productive, stable, resilient, independent, reliable).

But the extent at which innovation can take place in the redesign of current livestock system is constrained by their institutional context (**Figure 5**). By institutions, I mean markets, regulations, knowledge systems, principles and public or private organisations. For example, ecological intensification of pastoral systems cannot be regarded in isolation from the policy and legal environments in which pastoralist communities need to operate, especially when land tenure or access to natural resources are at stake (e.g., Dong, 2016). But on the other hand, consumers and value chains have a great power to stir change. Consider, for example, how the

FIGURE 6 | Commercial label of beef exported by a cooperative of livestock farmers in Argentina certified for birdlife-friendly grazing management practises by the Native Grasslands Alliance (*Alianza del Pastizal*). https://www.birdlife.org/grasslands-alliance/es.

uprising "grassland beef" market has influenced producers to adopt regenerative, sustainable and externally monitored practises of native grassland management and biodiversity conservation in different parts of the world (**Figure 6**, **Table 2**, and further: e.g., USA: discover.grasslandbeef.com; Australia: grasslandsbeef.com.au; etc.). There are also different ways in which large food retailers by themselves can positively influence sustainability (e.g., Macfadyen et al., 2016). Finally, and although this exceeds the scope of the present manuscript, I find it relevant

TABLE 2 | Examples of grassland beef value chains in South America and Europe, outlining their objectives and basic principles.

Initiative	Objectives	Basic principles
Grasslands Alliance (Argentina, Brazil, Paraguay, Uruguay)	Conservation of natural grasslands and their biodiversity Mitigation of greenhouse gas emissions Animal well-being during their life span in the grasslands Permanence and livelihoods of rural livestock families Health and safety conditions for the consumer Improve the commercial management of livestock on natural grasslands	I Compliance with procedures, records, resolutions and national regulations in force, with the proper health plan of the cattle backed by a professional and the labour regime of the employees in order II Nominal adherence of the participants to the Vision and Mission of the Grassland Alliance III Free access of the animals to sufficient sources of drink and shade IV Grass-based feeding with a tolerance limit of up to 30% concentrates, or the equivalent - in the animal's diet - up to 1% of live weight, in the total absence of feeding in confinement V At least 50% of the total surface of the property covered by natural grasslands
Baltic-Grassland Beef (Estonia, Latvia, Lithuania)	Animal-friendly, ecological cattle farming as close as possible to nature and sustained grazing during vegetation periods Production suitable to habitat (meat from roughage feed), grass and hay-based feeding of the animals Promotion of high-quality beef with optimum marbleization through selected beef cattle breeds Consolidation of mother cow husbandry Traceability on the farms and in transport and controlled slaughtering Reduction of climate impacts of imported beef	Basis: natural feed Roughage feed: grass, hay and silage Calves: milk from mothers No additional feeding of milk No genetic modified organisms (GMO) No chemical-synthetic performance additives No feed-urea No animal-based protein or fat No imported soy

Sources: Grasslands Alliance: https://www.birdlife.org/grasslands-alliance/grasslands-beef/en; Baltic-grassland Beef: http://balticvianco.com/bgb/baltic-grassland-beef.

to end by stressing that moving beyond anecdotal cases towards successful, broad and lasting transitions to ecologically intensive grazing landscapes requires innovation, policy and action also in the realms of natural resource and food system governance.

CONCLUDING REMARKS

Designing truly sustainable, multifunctional grazing landscapes requires expanding our thinking and narratives beyond narrow discussions informed by greenhouse gas emissions or carbon footprint assessments. The contribution of livestock to global warming and the need to reduce our consumption of animal products are undeniable. Yet the positive roles that grazing livestock can play in ecologically intensive management systems must also be acknowledged, particularly when thinking about strategies to curtail the current trends of biodiversity loss. Since the area of nature reserves and conservancies represents barely 5% of the terrestrial surface area of the globe, it is obvious that biodiversity conservation has to take place mostly in production landscapes. Grazing landscapes offer habitat for many species of plants, animals and microorganisms, but such habitats may be disrupted rapidly, either under industrial intensification or through overgrazing and land degradation in more traditional systems. Livestock systems differ widely in their current productive and environmental performances, and the trade-offs with maintaining viable rural livelihoods need to be quantified within each specific socio-ecological context. Although not addressed in this manuscript, trade-offs between short-term productivity and social well-being are also conspicuous in the livestock sector.

Agroecology provides the knowledge and guiding principles to design ecologically intensive grazing landscapes that can contribute to reducing the various production-environment trade-offs examined here. Yet this knowledge is not enough to transform landscapes if it is not conveyed to farmers, adapted and co-constructed with them, disseminated beyond the farm gate through multi-actor innovation platforms. Although inspiring examples of ecologically intensive grazing exist, and their numbers are growing, broad and lasting transitions at scale require conducive policy environments that address not only the production but also the manufacturing, trading and consumption of animal products. Current industrial livestock farms serve an inequitable global food system that, next to falling short of providing food for all, promotes the irresponsible overconsumption of cheap, unhealthy and unsustainable animal products in certain parts of the world, contributing to an obesity epidemic that affects 1,300 million people worldwide. Thus, "Feeding the world" should no longer be used as a supposedly altruist argument in favour of intensifying livestock production in unsustainable ways.

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Savannah Phenological Dynamics Reveal Spatio-Temporal Landscape Heterogeneity in Karamoja Sub-region, Uganda

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Phenological properties are critical in understanding global environmental change patterns. This study analyzed phenological dynamics in a savannah dominated semi-arid environment of Uganda. We used moderate-resolution imaging spectroradiometer normalized difference vegetation index (MODIS NDVI) imagery. TIMESAT program was used to analyse the imagery to determine key phenological metrics; onset of greenness (OGT), onset of greenness value, end of greenness time (EGT), end of greenness value, maximum NDVI, time of maximum NDVI, duration of greenup (DOG) and range of normalized difference vegetation index (RNDVI). Results showed that thicket and shrubs had the earliest OGT on day 85 $\pm$ 14, EGT on day 244 $\pm$ 32 and a DOG of 158 $\pm$ 25 days. Woodland had the highest NDVI value for maximum NDVI, OGT, EGT, and RNDVI. In the bushland, OGT occurs on average around day 90 $\pm$ 11, EGT on day 255 $\pm$ 33 with a DOG of 163 $\pm$ 36 days. The grassland showed that OGT occurs on day 96 $\pm$ 13, EGT on day 252 $\pm$ 36 with a total DOG of 156 $\pm$ 33 days. Early photosynthesis activity was observed in central to eastern Karamoja in the districts of Moroto and Kotido. There was a positive relationship between rainfall and NDVI across all vegetation cover types as well as between phenological parameters and season dynamics. Vegetation senescence in the sub-region occurs around August to mid-September (day 244–253). The varied phenophases observed in the sub-region reveal an inherent landscape heterogeneity that is beneficial to extensive pastoral livestock production. Continuous monitoring of savannah phenological patterns in the sub-region is required to decipher landscape ecosystem processes and functioning.

Keywords: conflict, drylands, grazing, mobility, pastoral

INTRODUCTION

Global environmental change, including climate change, is undoubtedly a pressing issue of global concern in recent times (Naeem et al., 2009; Bulkeley and Newell, 2010; Hussein, 2011). This in part is due to a rise in extreme events and associated threats to humanity, species and habitats (Birkmann et al., 2014; Allen and Allen, 2017; Ma et al., 2018). Climate variability and change in particular alters plant phenology because temperature tends to influence the timing of development, singularly and through interactions with other cues, such as photoperiods (Partanen et al., 1998; Fitchett et al., 2015; Suonan et al., 2019). In tropical regions and ecosystems, phenology dynamics are often less sensitive to temperature and photoperiods but more aligned to seasonal shifts in precipitation (Reich, 1995). These phenology patterns are attuned to environmental conditioning including the associated seasonality patterns (Cleland et al., 2007; Puppi, 2007). Shifts in plant phenology offers compelling evidence of ecosystem interactions with climatic patterns as well as with other components of global environmental change including the accumulation of atmospheric carbon dioxide (Cleland et al., 2007; Stocker et al., 2013). Phenology dynamics have important implications for biophysical and biogeochemical feedbacks to the climate system (Piao et al., 2019). Further, plant reproduction, population-level interactions, community dynamics and plant evolution and adaptations often influence ecosystem functions and services (Isbell et al., 2011; Maestre et al., 2012). These can, however, be altered by shifts in plant phenology (Peñuelas et al., 2013; Suonan et al., 2019).

Phenology examines organism-environment relationships using critical life cycle phenomena as the primary window (Liang and Schwartz, 2009). In situations where vegetation phenology varies at a scale relevant to the movements of individuals (e.g., dispersal or foraging ranges), such knowledge is essential to understanding processes and dynamics within such ecosystems (Cole and Sheldon, 2017). Analysis of phenology dynamics at landscape level is relevant because seasonal vegetation dynamics (including spatial and temporal patterns) within heterogeneous biophysical environments is critical for understanding the complex functioning of ecosystems. This includes the interactions of primary producers with seasonal and inter-annual environmental variability across landscapes (Liang and Schwartz, 2009). These heterogeneous phenological dynamics at regional and landscape-level are also important for animal populations (Haddad et al., 2011; Simms, 2013). This is because variation within a wide range of abiotic factors (e.g., soil moisture and nutrients, temperature, precipitation) often can cause plants at different locations to initiate growth at different times (Zheng et al., 2016). Evidence available indicates that plants and animals exhibit seasonal patterns in their activities. This is attributed to the fact that there is a seasonality in the suitability of their environment (Visser and Both, 2005).

In the Serengeti plains of Tanzania and Kenya, population viability of some grazers is directly influenced by access to patches of grassland that are varied in phenology as a result of spatial heterogeneity (Fryxell et al., 2005). Thus, plant phenology is an important parameter for showing long-term and seasonal variations in development patterns for both annual, biannual and perennial plants across different landscapes (Primack and Gallinat, 2017; He et al., 2018; Hegazy et al., 2018). Changes in phenological patterns of vegetation such as the rate and duration of photosynthetic activities, onset of greenness (OGT), end of greenness time (EGT) and duration of greenness (DOG) have the potential to serve as indicators of change in environmental quality including impacts on plant production (Vrieling et al., 2016; Ibrahim et al., 2018). Further, it is vital in detecting spatio-temporal variations in plant health and productivity (Tottrup and Rasmussen, 2004; Boke-Olén et al., 2016).

It is apparent that spatial heterogeneity in resources at landscape scale allows mobile consumers to compensate for temporal variability in resource availability at local scale (Fryxell et al., 2005). This is an important landscape characteristic of relevance to herbivores because it confers nutritional benefits by extending the foraging time as well as resource access at landscape level (Coogan et al., 2012). In water limited ecosystems especially semi-arid and arid areas, plant phenology is seldom synchronized across the landscape. However, it tends to vary asynchronously as a result of spatial and temporal variation in elevation, aspect, and weather (Chen and Pan, 2002; Hobbs et al., 2008). In these landscapes, wild herbivores, pastoralists and their livestock respond to gradients and pulses in forage quality and quantity by matching their distribution to spatially variable peaks and gradients in forage quality (Scoones, 1995; Hebblewhite et al., 2008). Responses occur in varying forms and at varying spatial and temporal scales. One adaptation strategy used by pastoral groups in response to this variability is to move across the landscape in search of abundant and nutritious forage (Ellis and Swift, 1988). These movements are key to sustaining the foraging and nutritional needs of livestock (Turner and Schlecht, 2019). They are critical for traditionally guided plant inflorescence-phenological dynamics (Dunning et al., 2016). They also form the basis for the ecological resilience of both pastoral livelihoods and rangeland ecosystems (Boles et al., 2019).

Accelerated environmental changes in pastoral landscapes in East Africa have been registered in the last two decades (Little, 1996; Boles et al., 2019). These changes include increased extreme weather events especially drought and flash floods (Ayal et al., 2018; Kimaro et al., 2018), land use land cover change and habitat fragmentation (Kimiti et al., 2018). These changes in part reflect policy shifts driven by outsiders that have historically viewed pastoralism as working against both environmental and development goals (Turner and Schlecht, 2019). In pursuit of "development," restrictions on pastoral mobility were imposed and at the same time significant promotion of sedentarisation and crop farming in much of Karamoja sub-region (Krätli, 2010; Egeru, 2016). Restrictions were imposed following the need to bring "peace" by controlling livestock theft within Karamoja and with neighboring communities and across Kenya, Uganda and South Sudan. In essence, the traditional pastoral Karamojong was "quarantined" to graze within the sub-region without being able to explore the traditional grazing pathways. Such restrictions of mobility of people and animals prevents herbivores and pastoralists from matching their distribution to the resources they require to survive and reproduce (Hobbs et al., 2008). Such interruptions on migratory pathways lead to profound effects such as landscapes becoming unsuitable to support people and animals (Fryxell et al., 2005) and localized degradation (Egeru et al., 2019).

Amidst these environmental changes, political orientations and re-orientations to what constitutes "development" in Karamoja and climate variability and change remain unresolved (Gray, 2000; Jabs, 2005; Krätli, 2010; Egeru et al., 2019). The intensity, frequency and shortened return time of extreme events (especially drought) is more pronounced today (Mubiru et al., 2018; Nsubuga and Rautenbach, 2018). Neighboring pastoralists from Kenya (Turkana, Pokot) have recently had to spend longer grazing time on the Uganda side than in previous grazing cycles. By spending a longer grazing time in Karamoja, they impose an additional challenge to people whose mobility is restricted. Accordingly, a paucity of information exists on vegetation dynamics in the region and how it might be able to support the internal mobility of pastoral groups within Karamoja as well as the external grazing pressure from Kenya and South Sudan. This study assessed savannah vegetation phenology with the aim of identifying spatio-temporal dynamics of plant activity in Karamoja sub-region. In doing so, we hold the assumption that the pastoral groups from within and outside the sub-region have only been able to maintain their livestock herds because of an inherent landscape heterogeneity. Further, Turner and Schlecht (2019) have opined that pastoral transhumance responds more to seasonal variabilities and spatial heterogeneities that display some predictable regularities across the landscape.

STUDY AREA

Karamoja sub-region is located in north-eastern Uganda and covers a total land area of 27,319 square kilometers. The sub-region is located between latitude 1°31′ to 4°N and longitude 33°30′ to 35°E. It is constituted by seven districts including: Kotido, Abim, Moroto, Amudat, Napak, Kaabong, and Nakapiripirit (**Figure 1A**). The sub-region consists of plains that rise toward the hilly terrain in the eastern parts of the region bordering the escarpment along the border with Turkana District of Kenya. The Kidepo Valley National park is part of the open grassland and woodland savannah ecosystems that predominate in the northern parts of sub-region. The landscape opens to the plains and low lands of central to western Karamoja, interrupted by Mt. Napak and isolated inselbergs and mountainous rises of the Iriri and Alekilek Mounts toward the border with the Teso sub-region to its west. In southern Karamoja in parts of Nakapiriti, occurs the Kadam Mountains that later open to the plains and flats in Namaalu with lush grassland ecosystem. This sub-region in Uganda is classified as semi-arid region and is known for its rainfall variability and intermittent droughts. Rainfall in the sub-region on average is about 800 mm with a non-uniform distribution ranging from 300 to 1200 mm in some parts of the sub-region (Egeru et al., 2014). Temperatures are considerably high and range from 28 to 32.5°C (maximum temperature) and from 15 to 18°C (minimum temperature) making evaporation rates in the sub-region similarly high.

The high evaporation rate in addition to the area sloping to the west leads to limited retention of water in the area as runoff rapidly accumulates in the lowland-wetlands of Teso, Lango, and Acholi sub-regions. The sub-region has had a marked irregularity in rainfall since the 1920s through 1940s and 1950s and intense droughts in the 1980s (Gulliver and Dyson-Hudson, 1967). This irregularity and unpredictability of rainfall patterns has exacerbated the fragility of local pastures and has required flexible and knowledgeable day-by-day herding decisions of pastoral households in the sub-region (Filipová and Johanisova, 2017). As a result, changes in the livelihood and lifestyle sources have occurred. For example, the International Organisation for Migration indicated that 40% of households in the sub-region now rely on natural resource extraction. Wood is used for charcoal production, topsoil is used to make bricks, and quarrying stone is used as a primary source of income and livestock management. Livestock, once dominant, is now a primary source of income for only 17% of the households in the sub-region. Despite this perceived income allocation sources, livestock remains a key livelihood asset and strategy as many households are striving to rebuild their livestock herds. In fact, Krätli (2010) indicated that the persistent food insecurity challenge in Karamoja is a livestock crisis indicator.

Traditionally, the Karamojong moved their livestock in a transhumant manner to manage grazing resources heterogeneity at landscape level. However, after the accumulation of guns in 1911 and pacification by the colonial administration from 1921, restrictions on movement in and out of Karamoja were imposed. These restrictions prevented the Karamojong from being able to freely graze their livestock within their traditional grazing lands (Knighton, 1990; Filipová and Johanisova, 2017). Most recently in the post disarmament exercise in 2007, a total ban on livestock from Karamoja leaving the sub-region was imposed. As a result, the pastoral households have had to manage their livestock numbers within the sub-region which has also had to accommodate the transhumant Turkana (herders from Kenya) who come to the sub-region as a dry season grazing ground (Egeru, 2016; **Figure 1B**). These dynamics have shaped resource use, governance and power relations. Where failure and competition for resources has been intense, violence and conflict over grazing lands and watering resources have been registered. This makes it critical to monitor vegetation dynamics in the sub-region.

MATERIALS AND METHODS

Data, Data Sources, and Analysis

Landsat imagery and Moderate Resolution Imaging Spectro-radiometer sensor images (MODIS) were obtained from USGS (https://earthexplorer.usgs.gov/). The land cover and Normalized Difference Vegetation Index (NDVI) extractions across 2000-2017 time series were, respectively, used with a 16-day composite (MODIS NDVI) at 250 meters spatial resolution.

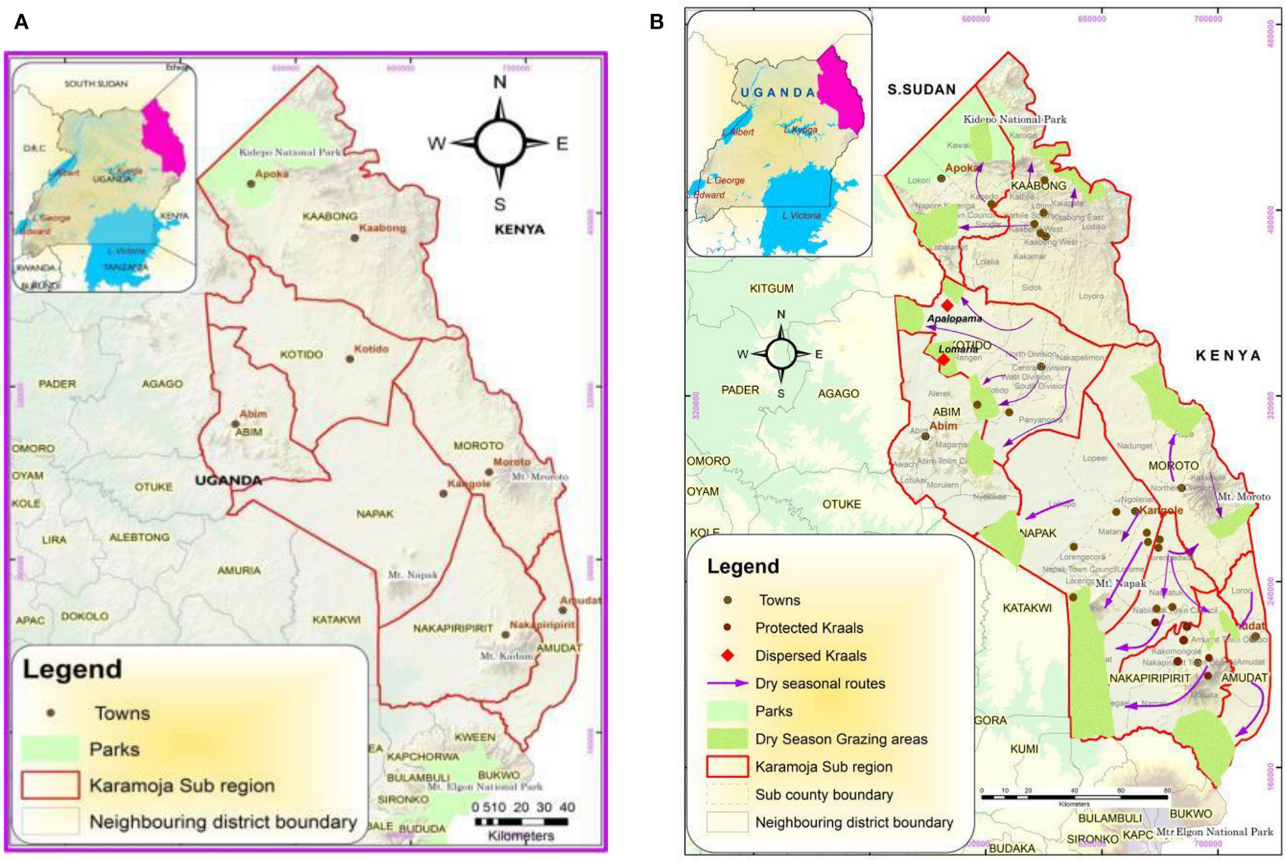

FIGURE 1 | (A) Location of Karamoja sub-region. **(B)** Dry season grazing areas and transhumance routes in Karamoja sub-region.

In addition to the relatively finer spatial resolution, MODIS data products also have lower noise from clouds or atmospheric haze, aerosols and negligible water vapor impacts (Huete et al., 2002).

NDVI Pre-processing

The NDVI was computed following an established standard NDVI derivation process. The NDVI was used because the normalization in the equation partially compensates for illumination conditions and surface terrain effects such as minimizing soil and reducing background effects (Lillesand and Kiefer, 1979; Lillesand et al., 2004). The NDVI data at 250 m spatial resolution and 16-day composite temporal resolution interval acquired by MODIS on the Terra platform (MOD13Q1) were used to derive the NDVI time series relevant for phenological analysis. The frequent revisits allows a greater opportunity for obtaining cloud free coverage during important phenological stages of land covers (Reed et al., 1994). This resulted in 23 composite NDVI images per year, providing a total time series of 391 NDVI images. MODIS NDVI imagery obtained were mosaicked, re-projected from Sinusoidal Projection to WGS84 area projection suitable for analysis using MODIStsp-R GUI package. MODIStsp enables performance of several preprocessing steps (download, mosaicking, projection, and resize) on MODIS data available within a given time period (Busetto and Ranghetti, 2016). For each of the selected homogeneous sites (**Figure 2**), MODIS NDVI time series data was extracted through a time series of 2000–2017. The mean NDVI time series data were extracted for all sampling fields of interest excluding pixels that were affected by cloud cover. These data provided the basis for examining the NDVI trends and the associated phenology metrics for the different land cover types.

Phenology Extraction

Both image-based and point-based NDVI time series were examined with respect to their growth and phenology patterns. However, only areas with relatively homogeneous land cover types (**Figure 2**) were selected to examine the variation in phenology and their response to climate variables. To sample the study area, several criteria were taken into account to ascertain representation of the major land cover types and avoid mixed or heterogeneous land cover patterns. Only areas that maintained their vegetation land cover types for the last 15 years were considered. Homogeneous land cover was identified by using stratified sampling and land cover strata were divided into homogeneous sub-groups for a better precision and accuracy. The community elders were involved to identify the different strata that have existed within a time limit of 15 years from each

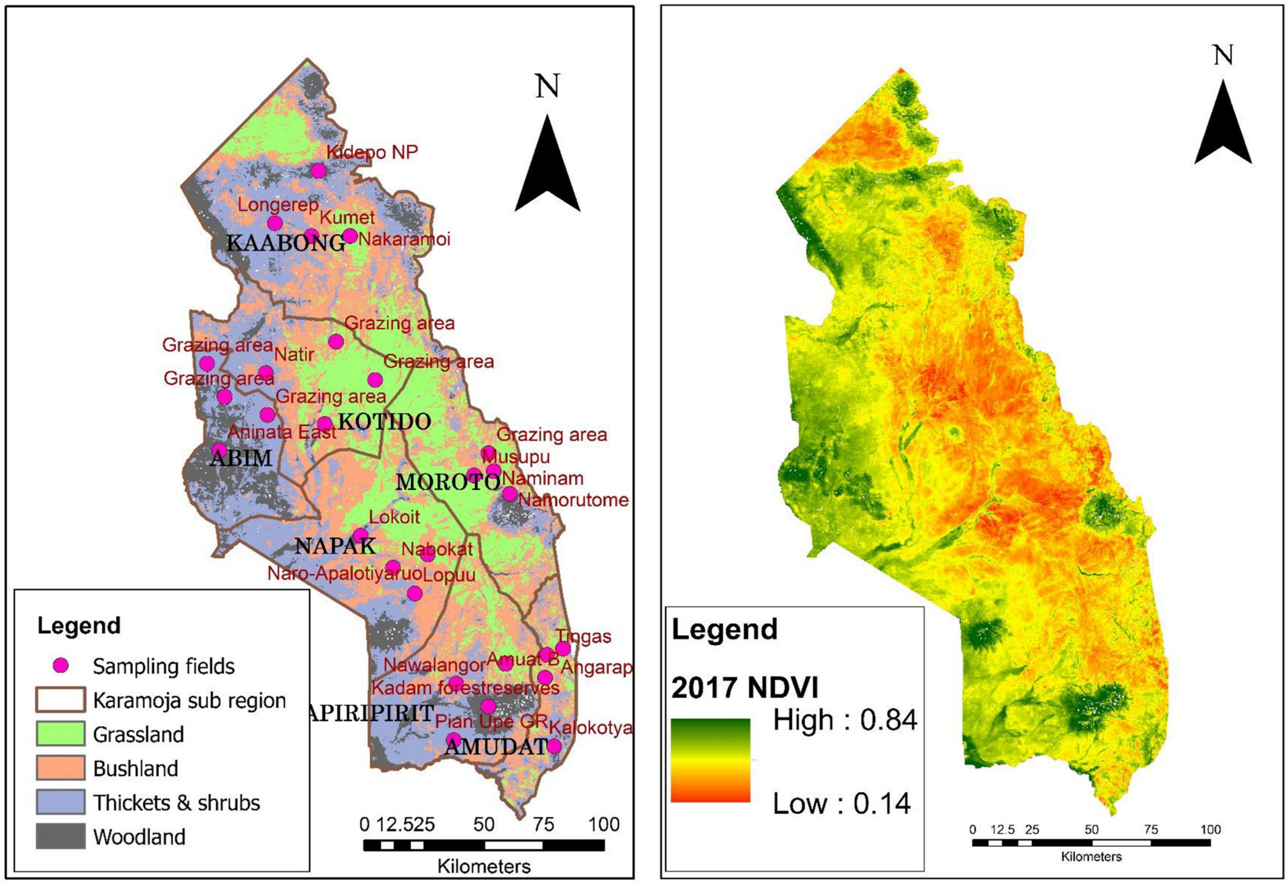

FIGURE 2 | Left-Locations of homogeneous sample fields and major land cover map derived from NDVI and right- NDVI values for the study region in 2017.

case study district. The NDVI time series data were used to derive land surface phenology-metrics measured in days.

The ArcMap cell statistics and zonal statistics were used to extract monthly mean NDVI values (**Figure 3**) that were used to extract savannah phenological characteristics within a time series of 2000–2017. A model builder was used to multi-task the processing of the numerous years (2000–2017). NDVI values were an input in the TIMESAT tool for extraction of the savannah phenological characteristics (Jönsson and Eklundh, 2004). Further detailed description of processes undertaken to execute a TIMESAT based analysis are described in **Appendix 1**.

Phenological Metrics

Phenological metrics of interest in this study are summarized in **Table 1** (Reed et al., 1994; USGS, 2011). The Onset of Greenness Time (OGT) is the beginning of measurable photosynthesis in the vegetation type canopy. It is obtained as the day of year identified as having a consistent upward trend in time-series NDVI. The Onset of Greenness NDVI (OG NDVI) is the level of photosynthetic activity at the beginning of measurable photosynthesis. As such it is the NDVI value associated with OGT. End of Greenness Time (EGT) is the end of measurable photosynthesis in the vegetation type canopy, corresponding to the day of year identified at the end of a consistent downward trend in time series NDVI. Time of Maximum NDVI (TMaxNDVI) is the time of maximum photosynthesis in the vegetation type canopy, which is the day of year corresponding to the maximum NDVI in an annual time series. Maximum NDVI (MaxNDVI) is the maximum level of photosynthesis activity in the vegetation type canopy, corresponding to the MaxNDVI in an annual time series.

Duration of greenness (DOG) is the length of photosynthetic activity in the vegetation type canopy, corresponding to the number of days from the OGT and EGT. According to Reed et al. (1994) the range in NDVI (RNDVI) is computed by subtracting the NDVI value of either onset or end of greenness, whichever is lower, from the maximum NDVI value. Rate of Greenup (RtUP) and Senescence (RtDn) were computed as straight-line slopes from onset to maximum and from maximum to the end, respectively (**Appendix 1**). A dynamic threshold algorithm was used to extract the phenology-metrics (Eklundh and Jönsson, 2017) which included temporal NDVI metrics (based on the timing of an event), NDVI value metrics (the NDVI value at which events occur) and derived metrics as categorized by Reed et al. (1994) for each of the savannah vegetation types

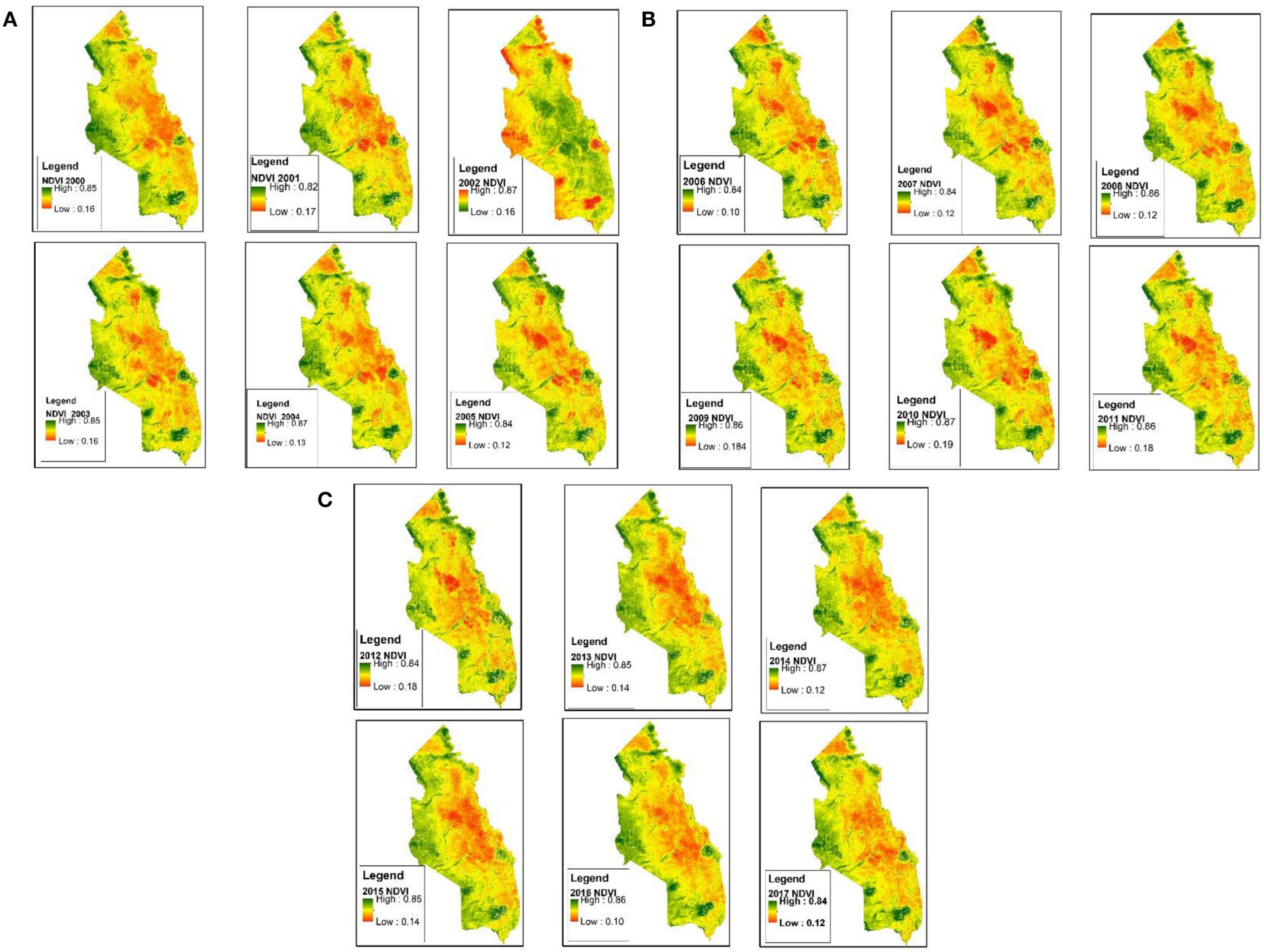

FIGURE 3 | (A–C) represent mean NDVI values for the period of 18 years between 2000 and 2017.

in Karamoja region. On this basis, the savannah vegetation multi-year mean per month was calculated for the period of 2000–2017 and smoothed to avoid outliers.

THRESHOLD VALUE OF SAVANNAH PHENOLOGY

Considering the range of savannah vegetation phenological characteristics, the onset of greenness NDVI threshold value was set to 20% of the distance between minimum and maximum NDVI during the rising levels (Zhang et al., 2015). The end of greenness was also determined in a similar manner (Song et al., 2011). The 20% threshold accounts for noise in the NDVI data and prevents the identification of false starts and/or end of greenness time (Van Leeuwen et al., 2010).

$$NDVI_{threshold} = NDVI_{min} + (NDVI_{max} - NDVI_{min})x20\% \quad (1)$$

The maximum NDVI ($NDVI_{max}$) with in the year was obtained, thereafter, during the NDVI rising stage, minimum NDVI ($NDVI_{min}$) was obtained and a 20% of the difference between $NDVI_{max}$ and $NDVI_{min}$ was set as the threshold ($NDVI_{threshold}$). Time of onset of greenness was defined as the date when NDVI reaches $NDVI_{threshold}$. The date when NDVI reaches to NDVI threshold for the first time was defined as time of onset of greenness. Time of end of greenness was defined in the same way during the descending stage (**Appendix 1**) for all vegetation types in the region as illustrated in 2001 for grassland vegetation (**Appendix 1**). Therefore, a threshold value of 0.1 NDVI as computed and obtained by several scholars (Lloyd, 1990; Reed et al., 1994; Jönsson and Eklundh, 2004; Song et al., 2011) was determined. This threshold was applied to all land cover types during the analysis.

RESULTS

Phenological Temporal Dynamics in Karamoja

Temporal indices including onset of greenness (OGT), onset of greenness value, end of greenness time (EGT), end of greenness value, maximum NDVI, time of maximum NDVI, duration of

TABLE 1 | Seasonal NDVI metrics and their phenological interpretation.

Metric	Phenological interpretation (Reed et al., 1994; USGS, 2011)
Temporal NDVI metrics	
• Time of onset of greenness	• Beginning of measurable photosynthesis
• Time of end of greenness	• Cessation of measurable photosynthesis
• Duration of greenness	• Duration of photosynthetic activity
• Time of maximum NDVI	• Time of maximum measurable photosynthesis
NDVI-value metrics	
• Value of onset of greenness	• Level of photosynthetic activity at beginning of greening season
• Value of end of greenness	• Level of photosynthetic activity at end of greening season
• Value of maximum NDVI	• Maximum measureable level of photosynthetic activity
• Range of NDVI	• Range of measureable photosynthetic activity
Derived metrics	
• Rate of green up	• Acceleration of photosynthesis
• Rate of senescence	• Deceleration of photosynthesis

greenup (DOG), and range of NDVI as phenological metrics of interest were computed for the four vegetation types: bushland, grassland, woodland, and thicket and shrub. Over the 18 years of analysis, there was high frequency of occurrence of an early EGT for bushland, thicket and shrub and woodland. Results of the respective vegetation cover showed that bushland on average has OGT occurring on day 90 ± 11, EGT around day 255 ± 33 with an average DOG of 163 ± 36 days. Meanwhile, maximum NDVI was 0.6 and the end value NDVI was 0.5 during the period of analysis (**Table 2**). A pronounced deviation in temporal phenology was observed in 2009 interrupting a relatively consistent trend in the measured metrics. There was a 67% probability of the OGT occurring in the fourth week of March and the first week of April (around the 90th day) with a 60% probability of maximum NDVI occurring in July. The green up ends around the 255th day, the second week of the month of September.

Grassland showed that on average OGT occurred on day 96 ± 13, EGT on day 252 ± 36 with a total DOG of 156 ± 33 days. It was observed that 2009 had the shortest photosynthesis activity of 74 days. Trend results showed a rapid increase in DOG in 2000, 2010, and 2017. Results also showed a relative consistency in phenological parameters from 2001–2007 with DOG ranging between 129–192 days. For all the years, the OGT ranged between day 79–105 and EGT ranged between day 222–291 except in the year 2000 where OGT was recorded on day 121 and EGT on day 325 of the year (**Table 3**). Onset of greenness were mainly observed in March and April (around day 96) with the highest occurrences in April (67%) in the first week of the month. Meanwhile, EGT exhibited strong variability across the months of July, August, October, November, and September with the highest (57%) chance of occurrence in the first week of September with a DOG of 156 days.

In the woodland the average OGT occurred on day 95 ± 16 with an onset of greenness value of 0.6 and EGT on day 253 ± 35 with a 0.7 end of greenness value. An overall DOG of 165 ± 47 days was observed. Compared to all other land cover types, woodland had a higher maximum NDVI value of 0.7 for the entire period of analysis (**Table 4**). The OGT, EGT and DOG held a similar trend for the period of analysis. Variation in the time of maximum measureable photosynthesis occurred between February and August in the woodland. The earliest onset of greenness time was revealed in 2006, 2001, 2011, occurring in the first 15 days of March. A relatively high (61%) probability of onset of greenness to occur was observed in March (61%) and in April (33%). End of greenness time varied across the period of analysis with occurrence in the months of July, August, September, October, and November.

In the thicket and shrub, OGT occurred around day 85 ± 14, EGT at day 244 ± 32 while DOG was 158 ± 25 days (**Table 5**). Onset of greenness occurred in March (67%) and April (33%) throughout the period of analysis. Variability in the duration of greenness across the time frame of analysis was observed. Results also showed that thicket and shrub had a 0.7 as the maximum green up value. About 75% of the peak NDVI in the thicket and shrub occurred in the third week of July. Like in the other vegetation types, end of greenness time occurred variably in July, August, and September. A higher frequency (57%) of occurrence was observed in September with 43% of the EGT occurring in the third and fourth weeks of September. On average, thicket and shrub have a greenness duration of 158 days. In **Appendix 2**, annual spatial representation of OGT, EGT, and DOG for 2000–2017 are provided for the Karamoja sub-region.

Spatial Phenological Patterns in Karamoja

We spatially represented the general phenological attributes between 2000 and 2017. We considered time of onset of greenness (OGT), end of greenness time (EGT) and duration of greenness (DOG) from the four major vegetation types: bushland, grassland, woodland and thicket and shrub. Spatially, the OGT and EGT in the sub-region can be represented into three categories, namely early, normal and late OGT/EGT. We found a significant difference in the total land area occupied by each of the vegetation cover types as well as a significant difference in the spatial coverage of the areas under early, normal and late OGT across the land cover types (**Table 6**). On the other hand, there were non-significant differences in spatial coverage across vegetation types as well as in the early, normal and late (ENL) periods for the EGT. Spatially, grassland cover a larger part of the study area (44%), followed by bushland (28%), thicket and shrub (21%) and woodland (7%). With the exception of the woodland, all the vegetation cover types revealed that their OGT occurred within a similar range. Intra-vegetation cover OGT spatial patterns indicated that 84% woodland areas posted an early OGT occurrence compared to bushland (38%), grassland (33%) and thicket and shrub (42%).

In the grassland (**Figure 4**), early photosynthesis (early OGT) activity occurred predominantly in central-eastern parts of Moroto and Kotido districts as well as in the eastern bounds of

TABLE 2 | Bushland phenological metrics for the Karamoja region in Uganda for the period 2000–2017.

Year	LULC	Max NDVI	Tmax NDVI (date)	NDVI threshold	Onset Date	Onset n^{th} day	Onset value	End (date)	End n^{th} day	End Value	Range NDVI	Duration (days)
2000	Bushland	0.55	Mid Aug	0.1	27-Apr	118	0.3	3-Sep	247	0.52	0.25	129
2001	Bushland	0.57	End Jul	0.1	20-Mar	79	0.35	2-Sep	245	0.5	0.22	166
2002	Bushland	0.50	Mid Jul	0.1	3-Apr	93	0.37	15-Aug	227	0.41	0.13	134
2003	Bushland	0.56	Early Jun	0.1	1-Apr	91	0.34	15-Sep	258	0.43	0.22	167
2004	Bushland	0.56	Mid May	0.1	1-Apr	92	0.37	12-Aug	225	0.46	0.19	133
2005	Bushland	0.59	Early Jun	0.1	29-Mar	88	0.36	5-Oct	278	0.44	0.23	190
2006	Bushland	0.55	Mid Jun	0.1	20-Mar	79	0.36	1-Sep	244	0.48	0.19	165
2007	Bushland	0.61	Mid Aug	0.1	13-Apr	103	0.43	22-Oct	295	0.45	0.18	192
2008	Bushland	0.61	Mid Jul	0.1	7-Apr	98	0.34	1-Oct	275	0.56	0.27	177
2009	Bushland	0.55	Mid May	0.1	1-Apr	91	0.35	7-Jul	188	0.44	0.20	97
2010	Bushland	0.58	Mid May	0.1	17-Mar	76	0.49	27-Oct	300	0.46	0.12	224
2011	Bushland	0.63	Mid Aug	0.1	27-Mar	86	0.34	27-Aug	239	0.62	0.29	153
2012	Bushland	0.68	Early Jul	0.1	1-Apr	92	0.36	3-Sep	247	0.6	0.32	155
2013	Bushland	0.65	Mid Apr	0.1	16-Mar	75	0.44	17-Aug	229	0.6	0.21	154
2014	Bushland	0.61	Early Aug	0.2	20-Apr	110	0.4	5-Oct	278	0.54	0.21	168
2015	Bushland	0.59	Mid May	0.1	26-Mar	85	0.37	20-Aug	233	0.4	0.22	116
2016	Bushland	0.59	Mid Jul	0.1	28-Mar	88	0.4	10-Sep	254	0.42	0.19	166
2017	Bushland	0.59	Mid Oct	0.1	25-Mar	84	0.34	27-Nov	331	0.51	0.25	247
Mean	Bushland	0.58	28% (Jul)	0.1	50% (Mar)	90.4	0.37	33% (Sept)	255.1	0.49	0.22	162.9
StDev	Bushland	0.04	N/A	0.02	N/A	11.3	0.04	N/A	33.2	0.1	0.1	36.2

TABLE 3 | Grassland phenological metrics for the Karamoja region in Uganda for the period 2000–2017.

Year	LULC	Max NDVI	Tmax NDVI (date)	NDVI threshold	Onset (date)	Onset n[th] day	Onset value	End (date)	End n[th] day	End value	Range NDVI	Duration (days)
2000	Grassland	0.5	Mid Aug	0.1	30-Apr	121	0.3	20-Nov	325	0.4	0.2	204
2001	Grassland	0.5	Mid Jul	0.1	20-Mar	79	0.4	1-Sep	244	0.4	0.2	165
2002	Grassland	0.5	Early Jun	0.1	26-Mar	85	0.4	3-Aug	215	0.4	0.1	130
2003	Grassland	0.5	Mid Jun	0.1	2-Apr	92	0.3	15-Sep	258	0.4	0.2	166
2004	Grassland	0.5	Mid May	0.1	1-Apr	92	0.3	2-Sep	246	0.4	0.2	154
2005	Grassland	0.5	Mid Jun	0.1	5-Apr	95	0.3	20-Sep	263	0.4	0.2	168
2006	Grassland	0.5	Mid Jul	0.1	30-Mar	89	0.3	10-Aug	222	0.4	0.2	133
2007	Grassland	0.6	Mid Jun	0.1	15-Apr	105	0.4	18-Oct	291	0.4	0.2	186
2008	Grassland	0.5	Mid Jul	0.1	27-Apr	118	0.4	15-Aug	228	0.5	0.2	110
2009	Grassland	0.5	Mid May	0.1	10-Apr	100	0.4	15-Jul	196	0.4	0.1	96
2010	Grassland	0.5	Mid May	0.1	15-Mar	74	0.5	18-Oct	293	0.4	0.1	219
2011	Grassland	0.6	Mid Aug	0.1	13-Apr	103	0.3	31-Aug	243	0.5	0.2	140
2012	Grassland	0.6	Mid Jul	0.1	4-Apr	95	0.4	15-Sep	259	0.5	0.3	164
2013	Grassland	0.6	Mid Apr	0.1	18-Mar	77	0.5	15-Jul	196	0.6	0.1	119
2014	Grassland	0.6	Mid Aug	0.1	18-Apr	108	0.4	25-Sep	268	0.6	0.2	160
2015	Grassland	0.7	Mid Jul	0.1	3-Apr	93	0.4	15-Aug	227	0.4	0.4	134
2016	Grassland	0.6	Mid Jul	0.1	28-Mar	88	0.4	2-Sep	246	0.4	0.2	158
2017	Grassland	0.5	Mid Aug	0.2	16-Apr	106	0.3	4-Nov	308	0.5	0.2	202
Mean	Grassland	0.5	28% (Jul)	0.1	67% (Apr)	95.6	0.4	39% (Sep)	251.5	0.5	0.2	156
StDev	Grassland	0.0	N/A	0.02	N/A	13.1	0.1	N/A	36.0	0.1	0.2	33.2

TABLE 4 | Woodland phenological metrics for the Karamoja region in Uganda for the period 2000–2017.

Year	LULC	Max NDVI	Tmax NDVI (date)	NDVI threshold	Onset Date	Onset n^{th} day	Onset Value	EGS (Date)	End n^{th} day	End value	Range (NDVI)	Duration (days)
2000	Woodland	0.7	Mid July	0.1	27-Apr	118	0.5	1-Sep	245	0.7	0.2	127
2001	Woodland	0.7	Mid Aug	0.1	15-Mar	74	0.5	20-Sep	232	0.7	0.2	158
2002	Woodland	0.7	End May	0.1	21-Mar	80	0.5	29-Aug	241	0.6	0.2	162
2003	Woodland	0.7	Early Aug	0.1	3-Apr	93	0.5	30-Sep	273	0.6	0.2	181
2004	Woodland	0.7	Mid Feb	0.1	10-Apr	101	0.6	15-Jul	197	0.7	0.1	91
2005	Woodland	0.7	Mid Jul	0.1	2-Apr	92	0.6	1-Sep	244	0.7	0.1	153
2006	Woodland	0.7	Mid Aug	0.1	5-Mar	64	0.5	12-Sep	255	0.7	0.2	192
2007	Woodland	0.7	End June	0.1	10-Apr	100	0.7	18-Oct	291	0.7	0.1	192
2008	Woodland	0.7	Mid Sep	0.1	28-Mar	88	0.7	15-Oct	289	0.7	0.1	201
2009	Woodland	0.7	Mid June	0.1	10-Apr	101	0.6	15-Jul	196	0.7	0.2	96
2010	Woodland	0.7	Mid May	0.1	10-May	130	0.7	20-Oct	293	0.6	0.1	164
2011	Woodland	0.7	Mid June	0.1	15-Mar	74	0.5	14-Oct	289	0.7	0.2	159
2012	Woodland	0.8	Mid Mar	0.2	7-Apr	98	0.5	18-Aug	231	0.8	0.3	134
2013	Woodland	0.8	Mid Apr	0.1	29-Mar	88	0.7	17-Aug	229	0.7	0.1	142
2014	Woodland	0.7	Mid Aug	0.1	17-Apr	107	0.6	20-Aug	233	0.7	0.1	289
2015	Woodland	0.7	Mid May	0.1	2-Apr	92	0.5	2-Aug	214	0.7	0.2	123
2016	Woodland	0.7	Mid Jul	0.1	20-Apr	111	0.6	10-Oct	284	0.5	0.2	174
2017	Woodland	0.8	Mid May	0.2	1-Apr	91	0.5	10-Nov	314	0.7	0.2	224
Mean	Woodland	0.7	22% (May/Aug)	0.11	61% (Apr)	94.6	0.6	28% (Aug/Sep)	252.8	0.7	0.2	164.6
StDev	Woodland	0.0	N/A	0.03	N/A	16.2	0.1	N/A	34.9	0.1	0.1	46.7

TABLE 5 | Thicket and shrub phenological metrics for the Karamoja region in Uganda for the period 2000–2017.

Year	LULC	Max NDVI	Tmax NDVI (date)	NDVI threshold	Onset Date	Onset n^{th} day	Onset value	End (date)	End n^{th} day	End value	Range NDVI	Duration (days)
2000	Thicket	0.6	End Jul	0.1	27-Apr	118	0.3	3-Nov	308	0.5	0.3	190
2001	Thicket	0.7	Mid Jul	0.1	17-Mar	76	0.4	18-Aug	230	0.6	0.3	154
2002	Thicket	0.7	Mid Feb	0.1	17-Mar	76	0.4	27-Sep	239	0.5	0.3	163
2003	Thicket	0.7	Early Jul	0.1	1-Apr	91	0.4	10-Oct	283	0.5	0.3	192
2004	Thicket	0.6	Mid May	0.1	2-Apr	93	0.4	13-Aug	226	0.5	0.2	133
2005	Thicket	0.7	Mid Jan	0.1	17-Mar	76	0.4	15-Sep	258	0.6	0.3	182
2006	Thicket	0.7	Mid Feb	0.1	16-Mar	75	0.4	18-Aug	230	0.6	0.3	155
2007	Thicket	0.7	Early Jun	0.1	10-Apr	100	0.5	27-Sep	270	0.6	0.2	170
2008	Thicket	0.7	Mid Jul	0.1	28-Mar	88	0.4	28-Aug	241	0.6	0.3	153
2009	Thicket	0.6	Mid May	0.1	13-Mar	72	0.4	10-Jul	191	0.5	0.2	119
2010	Thicket	0.7	Mid May	0.1	5-Mar	64	0.5	15-Sep	258	0.6	0.1	194
2011	Thicket	0.7	Mid Jul	0.1	10-Mar	69	0.4	27-Jul	208	0.7	0.3	139
2012	Thicket	0.8	Mid May	0.2	27-Mar	87	0.4	17-Sep	261	0.6	0.3	174
2013	Thicket	0.7	Mid Apr	0.1	15-Mar	74	0.5	7-Jul	191	0.6	0.2	117
2014	Thicket	0.7	Mid Jul	0.1	15-Apr	105	0.5	20-Sep	263	0.6	0.2	158
2015	Thicket	0.7	Mid May	0.1	25-Mar	84	0.4	27-Jul	222	0.5	0.3	138
2016	Thicket	0.7	Mid Jul	0.1	28-Mar	88	0.4	25-Sep	284	0.5	0.3	181
2017	Thicket	0.7	Mid Jul	0.1	3-Apr	93	0.4	25-Jul	225	0.7	0.3	132
Mean	Thicket	0.7	44% (Jul)	0.1	67% (Mar)	84.94	0.4	39% (Sep)	243.77	0.6	0.3	158
StDev	Thicket	0.0	N/A	0.0	N/A	14	0.1	N/A	32	0.1	0.1	25

TABLE 6 | Generalized linear models for spatial coverage and early, normal, and late (ENL) cluster for OGT and EGT.

Category	Df	Sum Sq	Mean Sq	*F* value	Pr (>*F*)
OGT					
Vegetation cover type	3	80,551,771	26,850,590	12.395	0.005
ENL cluster	2	31,809,366	15,904,683	7.342	0.024
Residuals	6	12,997,061	2,166,177		
EGT					
Vegetation Cover type	3	63,549,518	21,183,173	1.473	0.313
ENL cluster	2	9,418,360	4,709,180	0.327	0.732
Residuals	6	86,239,220	14,373,203		

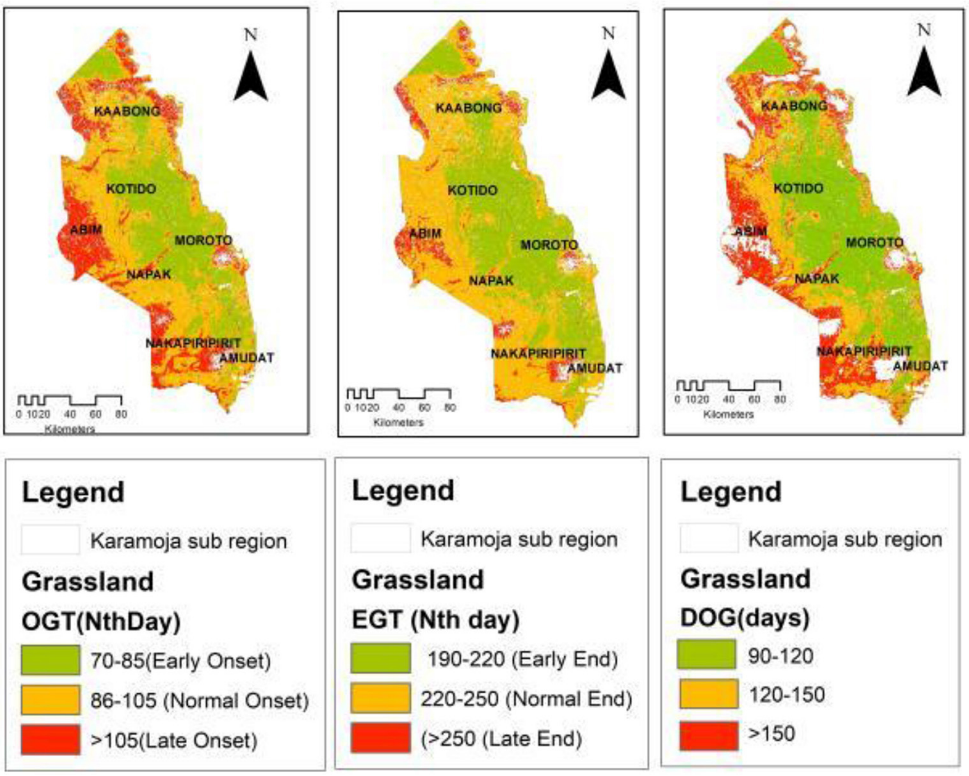

FIGURE 4 | Grassland OGT, EGT, and DOG spatial patterns.

Amudat district, south Karamoja. Some patchy observations of an early OGT were observed in parts of Kaabong district and further north in the Kidepo Valley National Park in Karenga district. Meanwhile, the late OGT was recorded predominantly in the western to southern parts of the study area mainly in the districts of Abim and Nakapiripirit and some patches of Napak district. These patterns are repeated in the EGT but with a significantly reduced presence of late EGT in the study area.

Bushland vegetation cover (**Figure 5**) occurs across most of the study area. Early OGT in Bushland vegetation closely follows the pattern set by grassland and dominates the central to eastern parts of the region with a late OGT mainly observed in the western parts of the region in the districts of Abim and Nakapiripirit. Spatially, intra-vegetation cover type EGT varied with bushland posting a 41% late EGT compared to grassland (49%), thicket and shrub (87%) and woodland (58%). However, inter-vegetation cover type spatial occurrence of the late EGT revealed that woodland (12%) had the largest area under late EGT followed by bushland (10%) and thicket and shrub (6%). Across all vegetation cover types, grassland experienced a larger spatial occurrence of early EGT (19%) compared to bushland (6%), woodland (2%) and thicket and shrub (1%).

The spatial patterns observed in the OGT and EGT have an influence on the observed patterns of the Duration of Greenness (DOG) time in the study region. Overall, the spatial distribution of DOG in the sub-region appeared to partition the sub-region into three key areas. This pattern is most pronounced in the grassland vegetation cover type (**Figure 4**) and the bushland

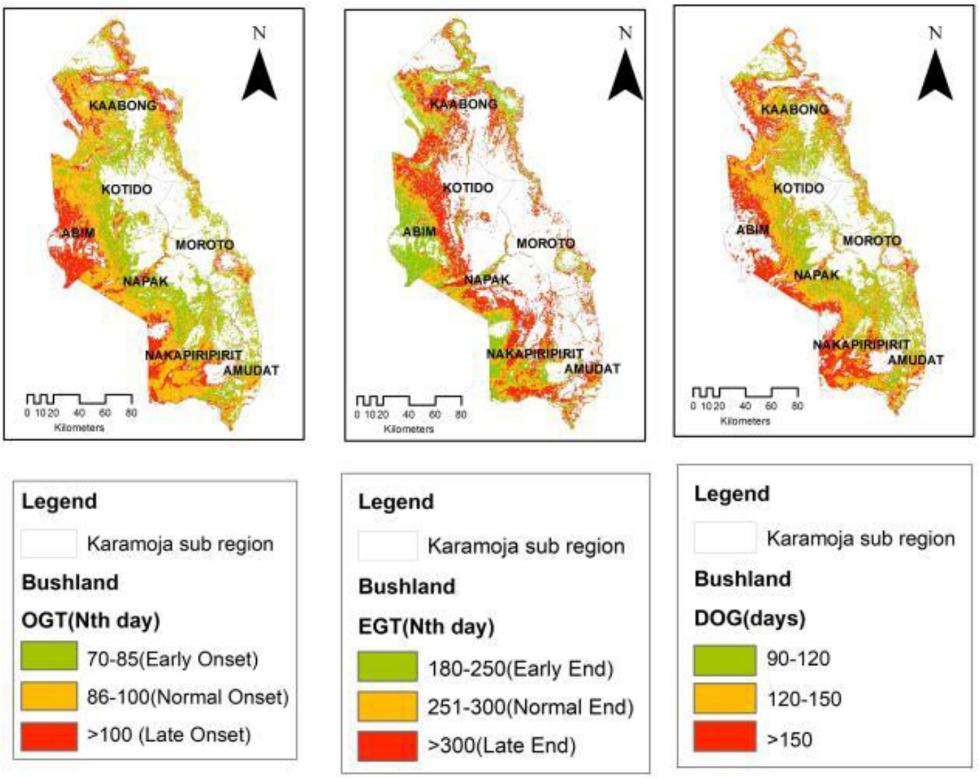

FIGURE 5 | Bushland OGT, EGT, and DOG spatial patterns.

that are widespread in the sub-region. In the grassland, areas with a shorter DOG (90–120 days; 44%) occurred mainly in the central to eastern parts of the sub-region (Kotido, Moroto and Amudat districts). The longer DOG (>150 days; 23%) was observed in the western frontier (Abim and Napak districts) and some patches in the north and northeastern (Kaabong-Karenga districts) as well as in the southwestern parts (Nakapiripirit and Nabilatuk districts). These spatial patterns observed in the grassland were repeated in the bushland with a DOG > 150 days (29%) and was most commonly observed in the western frontier of the sub-region. While the woodland (**Figure 6**) had areas with DOG > 180 days (11%), these appear to be confined to the highland areas in the sub-region, in areas such as Mt. Kadam (south), Mt. Moroto (east), Mt. Labwor (west) in Abim, and Mt. Morungole (north east apex). Thicket and shrub presented two cluster categories of DOG (**Figure 7**). There were those within the 100–130 days (21%) and others within 131–170 days (79%) which also had a larger spatial coverage. Across the four vegetation cover types, grassland (DOG 90–120 days) and thicket and shrub (DOG 131–170 days) had the most pronounced signals at 19 and 18%, respectively.

Relationship Between Rainfall and Vegetation Phenology

Results revealed that grassland, bushland, woodland and thicket and shrub had a strong positive correlation with rainfall throughout the years of analysis (**Appendix 3**). The strongest response signal was observed in bushland ($r = 0.70$), grassland ($r = 0.72$), and thicket and shrub ($r = 0.70$) while woodland posted a correlation of $r = 0.6$ for the period of analysis (2000–2018). Our results of the phenological patterns matched against rainfall-seasonal dynamics (**Figure 8**) revealed that there was a positive association between the rainfall-derived end of growing season (EGS) and vegetation-derived end of greenness (EGT) time as well as length of growing season (LGS) and duration of greenness time (DOG) in the bushland vegetation. For all the other three vegetation cover types (grassland, woodland, thicket and shrub), we also observed a positive relationship between the EGS and respective EGT for each vegetation cover type although the values were statistically non-significant. We also observed a positive association between the start of growing (SGS) and Onset of greenness time (OGT) in the thicket and shrub but grassland, bushland, and woodland posted non-significant negative associations (**Figure 8**).

DISCUSSION

In this study, we assessed the phenology of savannah vegetation to identify the spatio-temporal dynamics of plant activity in the Karamoja sub-region. We observed variability in phenological metrics of the four savannah vegetation cover types, namely

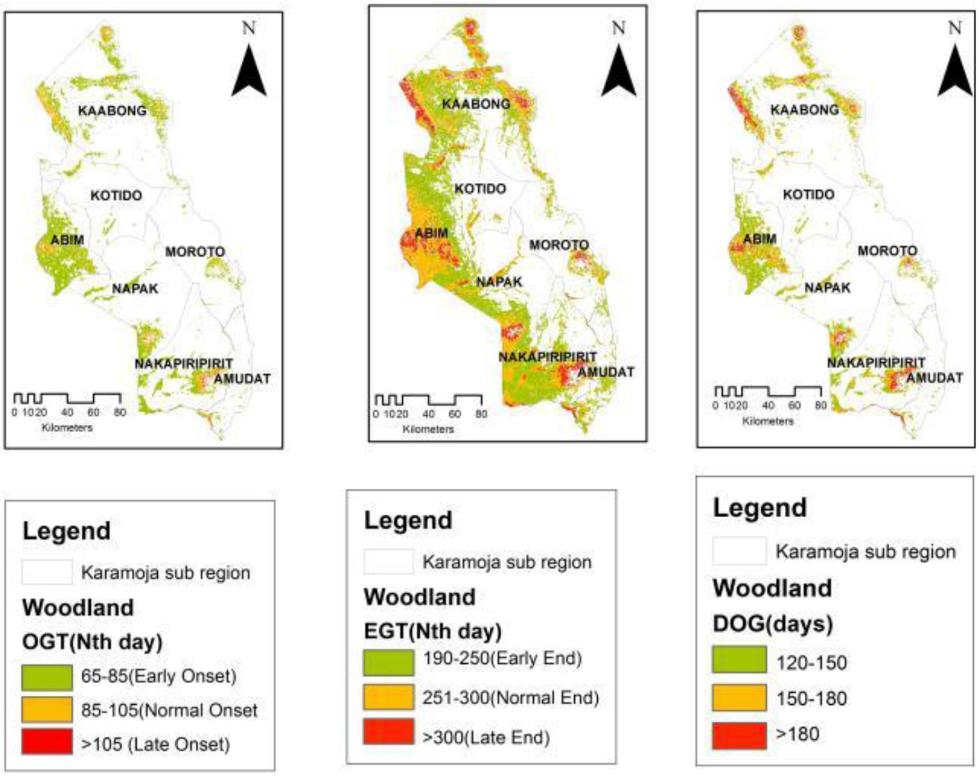

FIGURE 6 | Woodland OGT, EGT, and DOG spatial patterns.

bushland, grassland, woodland and thicket and shrub. Both intra-annual and inter-annual dynamics in phenology were evident across the Karamoja landscape. The observed intra and inter-annual variations point to the existence of different physiological mechanisms of plant growth, nutrient cycling, and abiotic processes including those influenced by geomorphology, soil fertility, climate, and disturbances such as fire which is commonly associated with semi-arid landscapes (Myoung et al., 2013). Fire as a disturbance in semi-arid areas plays an intrinsic role in shaping biophysical attributes of savannah ecosystem by limiting biomass below its climatically determined potential (Singh et al., 2018). In addition to other biotic and abiotic factors, above-ground phytomass disturbance and variable plant responses to fire, leads to differences in the dynamics of plant phenology across semi-arid areas landscapes (Snyman, 2004; Tokura et al., 2018; Richter et al., 2019). These disturbances appear to have been responsible for a lower signal strength in the sub-region in 2009. This lower signal strength in 2009 is traceable to the 2009/2010 drought episode. Using satellite-based indices derived from NDVI, Nakalembe (2018) identified extreme drought in 2009 over the sub-region.

Whereas we anticipated to find intra and inter-annual variability in vegetation phenology primarily because of the inherent climate variability (Egeru et al., 2014, 2019) in the sub-region, the specific metrics such as OGT, EGT, and DOG posited unique patterns within each of the main vegetation types. However, all of these savannah vegetation types showed OGT signals within late March and early April with a probability ranging between 67 and 75%. This falls within the main rainfall period in the sub-region and in most of the semi-arid areas of Uganda. Variability in the onset for the March-May rainfall and green-up has been observed to be variable across most of Uganda from year to year and in several occasions has been observed with some delays of even up to 30 days, thus starting in mid-April instead of mid-March (Mubiru et al., 2012). Such variability appears to have been captured by the vegetation greenup signals in the current study. This study has further demonstrated that savannah vegetation responds to rainfall signals but at varying levels which is demonstrated by lag-time of nearly 3 weeks observed in this study.

The variability observed in OGT with respect to vegetation types could perhaps be explained by specific vegetation response to climate parameters especially rainfall (Kang et al., 2018). Thus, the lag-time seen in this study between the different vegetation types within a 3 week range could indicate a critical threshold required for the vegetation to grow leading to the commencement of the OGT between the thicket and shrubs, grassland and woodland. Previous studies have shown that vegetation grows when a critical threshold is met based in part on cumulative rainfall, the proportion of annual average rainfall and relative soil moisture index (Lyamchai et al., 1997; White et al., 1997; Tao et al., 2017). This is particularly important in semi-arid

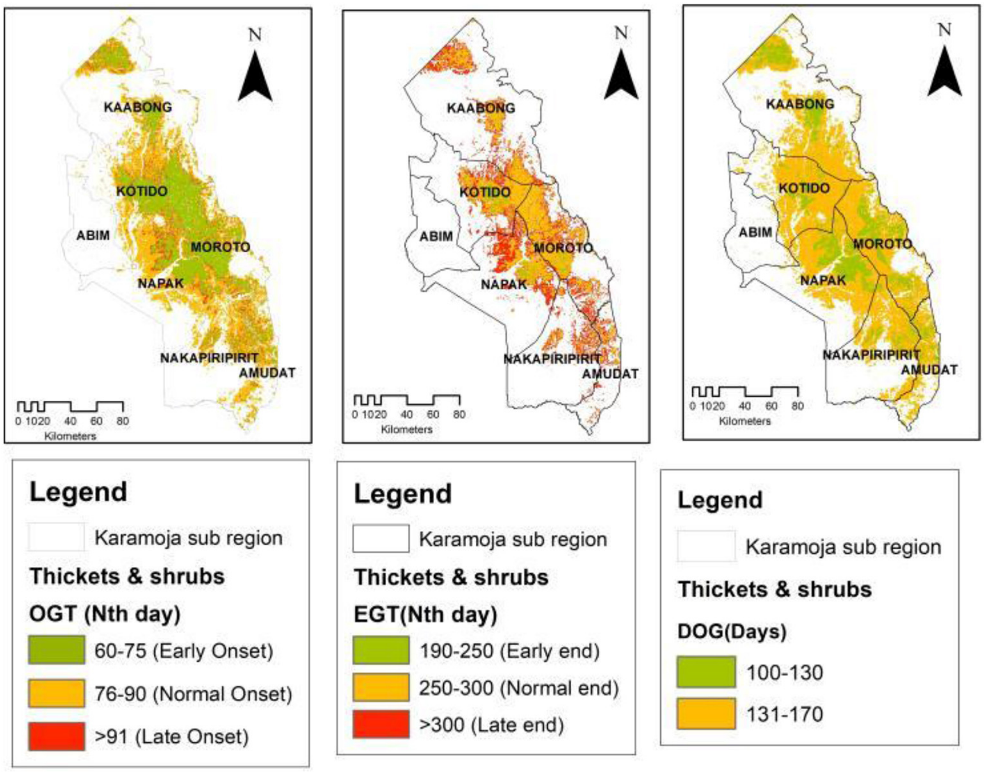

FIGURE 7 | Thicket and shrub OGT, EGT, and DOG spatial patterns.

regions of Africa where cumulative rainfall stimulates vegetation green-up. The Onset observed in this study corresponds to earlier analysis of vegetation phenology over the Horn of Africa in which Zhang et al. (2005) observed a first set of onset occurring in April, with a second one in September. Further, Vrieling et al. (2013) have suggested that a delayed onset of green-up is logical because there is often a lag time between the onset of rainfall and green-up. It is however important to note that contrary to the expectations that grassland would experience an early OGT, it was the thicket and shrubs and woodland that had an early sprouting. We attribute this development to a pre-rain green-up that has previously been documented in African savannahs (Adole et al., 2018). It also strengthens the understanding that vegetation growth onset in semi-arid regions is more often than not biome-dependent. This was stressed earlier by Pau and Still (2014) who pointed out that the length of the growing season varied between different vegetation types.

Although we observed a nearly consistent pattern in onset in this study, the intra-vegetation cover type variability was a stronger signal for heterogeneity of livestock grazing resources in the sub-region. The strong varied spatial occurrence of green-up within and across vegetation cover types within the early, normal and late green-up delivers grazing resources at different periods of time and at different locations in the sub-region. This is vital for differentiated pastoral utilization of landscapes. For example, we have shown that woody vegetation cover (woodland, thicket and shrub, and bushland) generally have earlier green-up compared to grassland. In parts of the Horn of Africa that are semi-arid, it has already been shown that even within a dry-spell, vegetation and especially trees and shrubs, remains green and abundant (Vrieling et al., 2013). According to Ellis and Swift (1988) pastoralists have relied on these varying forms of vegetation response and at varying spatial and temporal scales to graze their livestock across landscapes and have thus formed a strong basis for the resilience of pastoral livelihoods and rangeland ecosystems (Boles et al., 2019).

Variability is inherent in the sub-region's phenology. We have observed varied commencements for EGT to occur between July-November. Taken across the vegetation cover types, we did not find this EGT significantly different from each other however the intra-vegetation cover type variability was pronounced. A late EGT for grassland (49%), thicket and shrub (87%) and woodland (58%) provides support for the idea that heterogeneity in livestock resources exists across the landscape. It has been observed that woody vegetation with leafy fodder is often more reliable for livestock nutrition than grasses (Opiyo et al., 2015). In this study, both thicket and shrub and woodland tended to have a late EGT thereby becoming important grazing points during dry conditions. Further, this variability often dictates seasonal movements between base locations observed by Turner and Schlecht (2019) among pastoral communities in sub-Saharan Africa.

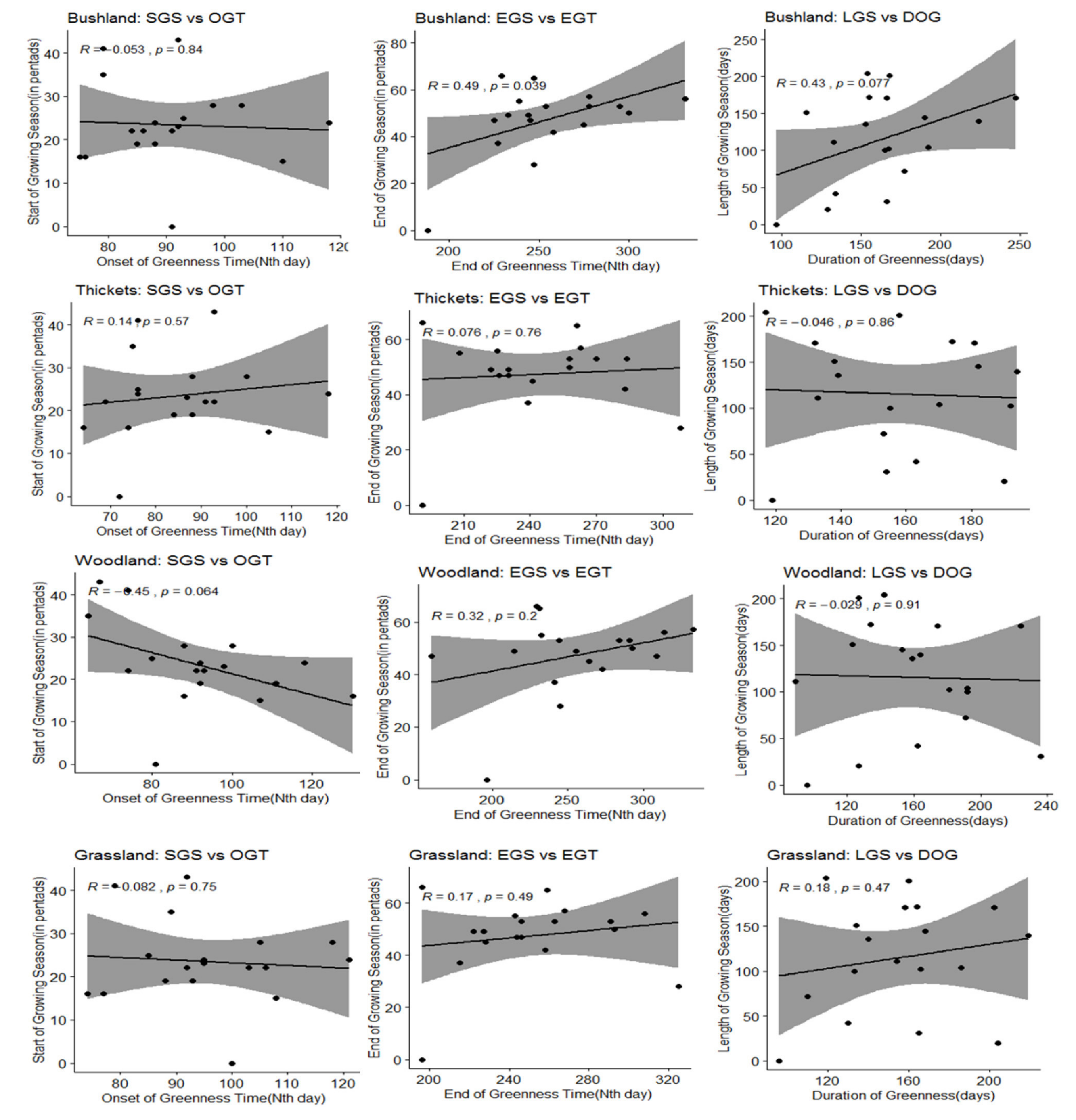

FIGURE 8 | Relationship between rainfall SGS, EGS and LGS and vegetation phenological parameters.

We also observed varying duration of greenness time (DOG) which occurred as a direct result of the patterns of OGT and EGT. Accordingly, while thicket and shrubs green up much earlier, the woodland had a longer duration of greenness (DOG) compared to all other vegetation types. In their study in southern Africa, Dekker and Smit (1996) observed similar patterns with grassland having short life cycles. Grassland have also been shown to be less adaptive to periods of moisture deficits (Puppi, 2007; Rather et al., 2018). We have also seen that the DOG appears to partition the sub-region into three key areas namely eastern, central and western Karamoja corridors with the western areas generally having a longer DOG occurrence, followed by central and eastern having a shorter DOGs for most of the vegetation cover types. These observed patterns do align with the rainfall dynamics and gradients in the sub-region. For example, locations in the western to southern Karamoja that exhibit a longer DOG correspond to lowlands and some highland areas of Mt. Labwor, Mt. Napak and Mt. Kadam that receive relatively higher rainfall in the sub-region (Egeru et al., 2019). Similarly, patches observed in eastern Karamoja occur around Mt. Moroto area as well as in the Mt. Morungole highlands of northern Karamoja. These areas have also traditionally served as important dry season grazing grounds in the sub-region (OCHA, 2010; see **Figure 1B**). Owing to these patterns, these areas have through historical time served as dry season grazing landscapes for the Karamoja sub-region. Throughout historical times, these areas of supposed resource abundance have dictated relationships, alliances, power and conflict in the sub-region (Ocan and Ocan, 1994). Given recent developments in the sub-region which restrict the outward mobility from Karamoja to neigbouring sub-regions for grazing, the locations with extended duration of greenness have become increasingly important grazing locations.

Implications for Pastoral Transhumance in Karamoja Sub-region

Pastoral production strategies in East Africa have through historical time relied on opportunistic and extensive livestock transhumance in heterogeneous landscapes (BurnSilver et al., 2004). Transhumance responds to more seasonal variabilities and spatial heterogeneities across the landscape in response to the need for sustained livestock nutrition (Turner and Schlecht, 2019). This study has shown five important facts that point to the importance of landscape heterogeneity and therefore differentiated availability of livestock grazing resources in time and place. First, the onset of greenness varies across space and time and within vegetation cover types. Second, the end of greenness time, although non-significant across vegetation types, displays a strong intra-vegetation cover type variability in terms of early, normal and late end of greenness measures. Third, areas of the longer duration of greenness time are consistent with dry season grazing locations in the sub-region. Fourth, woody vegetation has a longer duration of greenness time but also generally has an earlier onset of greenness across the sub-region. Fifth, the sub-region's onset of greenness time and end of greenness time partitions the sub-region into three distinct zones which may be referred to as the eastern, central and western frontiers with the eastern frontier generally having a shorter duration of greenness and the western to southern frontiers having a longer duration of greenness.

These five facts raise three key implications for pastoral transhumance when these are taken together with other macro-scale political and socio-economic factors that are shaping and re-shaping pastoral dynamics in the sub-region. First, intra-sub-regional pastoral mobility will continue in response to the heterogeneity of livestock resources brought about by the inter and intra-variability in vegetation cover and biomass; second, the pronounced early onset of greenness and late duration of greenness by woody vegetation (woodland, bushland and thicket and shrub) in the sub-region could drive the pastoral communities to shift to adopting browser based livestock species such as camels and goats. Already, increased proliferation of camels from Kenya to Karamoja in southern Karamoja in parts of Amudat brought by their Pokot kinsmen (Nampala, 2013) and among the Matheniko communities of Moroto district brought by their Turkana kinsmen has been on the increase. Owning camels in the sub-region for example has been linked to a 20% increase in household resilience (Asiimwe et al., 2020). Third, the areas with extended duration of greenness will remain important dry season grazing grounds in the sub-region. These will shape local alliances among tribal groups, maintenance of peace and/or potential conflict hotspots as well as land use competition between grazing and crop cultivation in the sub-region. As the pastoralists in Karamoja are incrementally sedentarising, areas posting greater duration of greenness, and thus a longer growing season duration, are also targeted for crop production development. It is predicted that this will only intensify land use change conflicts in the future.

CONCLUSION

We analyzed the phenological dynamics of the Karamoja sub-region using a suit of phenological metrics across four vegetation types (bushland, grassland, woodland, and thicket and shrub). We observed intra and inter-annual variability in key metrics including OGT, EGT, and DOG during the period of analysis. There was an apparent consistency in the onset of greenness time around late March and first week of April across the study area. However, woodland and the thicket and shrubs showed a relatively earlier OGT in the sub-region which was most pronounced around the districts of Napak and Nakapiripirit. This could point to a pre-rain green-up that has also been previously documented in other studies associated with savannah ecosystems across Africa. Within the variable DOG, we found that grassland vegetation was associated with a shorter DOG while woodland had a longer DOG across the sub-region. The highland areas in Karamoja region experienced longer periods of greenness compared to low-lying areas. Longer and shorter DOG was associated with longer and shorter length of growing season, respectively. Owing to the inherent variability in space and time observed in the sub-region, we confirm that the sub-region has an inherent heterogeneity. This heterogeneity could be important to livestock herders in the sub-region particularly because the EGT is spread variably across different landscapes and vegetation types. This could be aiding pastoral mobility and supporting their ability to meet their livestock nutrition across the year. Based on apparent variability and consistencies-regularities observed in this study, a practical direction should be to understand how these patterns are shaping pastoral mobility patterns in the sub-region. Further, an examination of how local institutions (both state and non-state) are helping to support mobility within a complex system of variability and heterogeneity, statehood, competing land uses, alliances and a rapidly evolving yet dangerous notion of modernization by eliminating mobility in the sub-region, are requisite conversations.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

AUTHOR CONTRIBUTIONS

AE and JM conceptualizing. AG and BB providing technical back stopping on data analysis and imagery. AE, JM, DK, and AS imagery processing and drafting manuscript. JN overall project coordination. AE funds sourcing and field activity arrangements. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2020.541170/full#supplementary-material

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REVIEW
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Review: Impact of Food and Climate Change on Pastoral Industries

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The industrialization of agriculture based on inexpensive fossil fuels allowed for unprecedented levels of food production and population growth, but simultaneously contributed to a threat to food systems and population well-being: climate change. This paper analyses the impacts and adaptations available to the world's pastoral production systems including potential mitigation and adaptation strategies. The current food system is under pressure to satisfy the needs of the increasing population with already limited natural resources particularly land and water, and now increasingly under pressure due to climate change. Increasing incomes from greater number of people have increased demand for animal source foods. As a result, domestic livestock numbers are rising, particularly in low-income countries with greater dependence on pasture for animal feed. The carrying capacity of pastured land is limited; therefore, increasing animal numbers may cause environmental degradation and loss of productivity from pastoral industries. In some countries, the increasing demand has prompted some to burn forestlands and convert them into crop production, and after the land is degraded into pasture mainly for raising large ruminants. Changes in atmospheric carbon dioxide levels and ambient temperatures are predicted to make a number of changes to the growth of herbage for animals. Several strategies can be implemented to optimize the pasture-based food system, including choosing the right breed, improving reproductive efficiency, improving grazing management, and maintaining an animal feed base. The global challenge is to meet our food production needs while sustaining our environment. Producers in all income categories have a role to play in adapting to these challenges.

Keywords: adaptation, environment, greenhouse gas, livestock, pastoralism

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INTRODUCTION

Pastoralism, herding of large animals as a means of livelihood, is one of the oldest viable and potentially sustainable systems, if properly managed [International Fund for Agricultural Development (IFAD), 2008; Dyer, 2016]. Pastoralism exists in about 100 countries across all continents except Antarctica [Food and Agriculture Organization of the United Nations (FAO, 2001)]. Pastoral livestock systems utilize 25% of terrestrial land on earth (mostly drylands where conventional farming is limited or not feasible) producing about 10% of meat consumed worldwide and supporting 200 million households (Blench, 2001). Pastoralism has a huge impact on the economies of several countries especially in Africa and Central Asia. For instance, in Africa pastoralism contributes 10 to 44% of gross domestic product (African Union, 2010). In addition to economic importance, pastoralism occurs in socio-cultural hotspots (e.g., world heritage sites), provides ecosystem services (e.g., maintaining and even enhancing rangeland biodiversity), and maintains ecological integrity (e.g., act as a carbon sink) (Stolton et al., 2019).

Pastoralism has considerable economic ecological, and socio-cultural importance (summarized in **Figure 1**). Pastoralists make their livelihoods in some of the harshest of conditions and unpredictable climatic conditions, however, they face challenges due to demographic, economic, political and climatic changes (Dong et al., 2016). Since the industrial revolution, the concentration of greenhouse gases (GHG) in the atmosphere have increased resulting in global land surface temperature rise, sea level rise, and drought in some areas (e.g., West Asia, North-Eastern Asia). On the other hand, climate change has increased precipitation, frequency and intensity of floods, storms and wildfires, and emergence of new diseases for crops, livestock and humans [Intergovernmental Panel on Climate Change (IPCC), 2019]. Climate change is negatively affecting food security particularly in pastoral systems of African drylands and mountainous regions of Asia and South America either directly or indirectly affecting both crop (e.g., increasing or decreasing yield of some crops depending on latitudes) and livestock (e.g., lower growth and production of pastoral livestock system) production (IPCC, 2019). Logically, pastoral livestock production is exacerbating climate change because agriculture (including forestry and land use) and livestock production represent 23 and 14.5% of total anthropogenic GHG emissions, respectively (Gerber et al., 2013; IPCC, 2019). Nevertheless, pastoral system can be a sink of GHG if it is well-managed without modifying landscape and natural ecosystems (e.g., clearing forests or modification of natural ecosystems). Additionally, global population is predicted to exceed 9.7 billion by 2050 (UN, 2019). Most of the population growth will occur in low-income countries primarily in Africa and Asia. This increment in global population along with increasing living standard and incomes is increasing global food demand. For instance, milk and meat demand will increased about 60% by 2050 (Brian, 2015). This will not only force intensification of crop and livestock production but will increase climate change risk due to land use changes and increasing total GHG emissions. Thus, it is of utmost importance to understand the two-way interactions between climate change and pastoral livestock production systems. The objective of this review is to (1) summarize and critically analyze the current literature focusing on the impact of food production and climate change on the pastoral livestock industry at a global scale, and (2) discuss the potential mitigation and adaptation strategies of climate change risks for pastoral industries.

DEFINITION, FORMS AND GEOGRAPHICAL DISTRIBUTION OF PASTORALISM

Pastoralism, found mainly in low-income countries and sometimes in isolated less developed regions of high-income countries, is a form of livestock production where human activity and nature affect each other. Pastoralism is the caring and herding of large animals in dryland areas when looked at through a production perspective (Dong et al., 2016). From a livelihood perspective, pastoralism is the subsistence and successful living through herding livestock in less productive lands (IFAD, 2008). "Pastoral system," an alternative term for pastoralism, is the livestock production system where grazing of animals is the major land use. There are at least five different forms of pastoralism depending on herd mobility pattern, resource use and income generated from livestock and livestock products (**Table 1**; Dong et al., 2016). Nomadic and transhumant pastoralism are the most common forms. Nomadism is practiced mainly in dry and high non-arable lands with low rainfall and harsh climatic conditions. There are about 30 to 40 million nomads living mainly in Mongolia, Russia, China, Eastern Europe and Central Asia. Nomads live in tents and move between 10 and 1,000 km annually. Transhumant pastoralists live in permanent homes in all pastoral regions across continents and move their animals between summer and winter pastures annually. Vertical transhumance is typically practiced in mountainous regions (e.g., Bavaria in Austria, Swiss Alps), while horizontal transhumances is practiced in plain land areas (e.g., Mongolia). Horizontal pastoralism is more vulnerable to climatic or socio-economic changes than vertical pastoralism (Dong et al., 2016). Agro-pastoralism is a form of pastoralism in which most of the family income is generated from cultivating crops compared to pastoralists that generate more than 50% of family income from livestock and livestock products (IFAD, 2008). Although the focus of this review is nomadic and transhumant pastoralism, the review briefly discusses agro-pastoralism and silvo-pastoralism due to its dominance and importance for certain regions such as South-Asia and Latin America. Currently, pastoralism predominantly exists in Sub-Saharan Africa, Central Asia (including Himalayas), and Australia, some part of Northern Europe, Central South America and Western North America. Although distribution of livestock species depends on geographic location, climatic condition and history of pastoralism, the most common species of pastoral livestock at the global scale are cattle, goats and sheep. Nevertheless, roughly 15 different livestock species are found in different pastoral forms and geographic regions (**Table 2**).

POPULATION GROWTH, FOOD PRODUCTION AND CLIMATE CHANGE

Anthropogenic GHG emissions have now reached the highest levels in recent history with clear evidence of human influence on climate change (IPCC, 2019). At current global food demand, about 25% anthropogenic GHG emissions arise from food production whereas agriculture accounts for 70% of freshwater use globally (IPCC, 2019). However, compared to intensive systems, pastoral livestock production systems utilize less water due to less reliance on cultivated feeds and fodders, resulting in less fossil fuel use (Steinfeld et al., 2010). Pastoral systems produce animal foods using forages and thus utilize much less human-edible protein compared to intensive production systems (Steinfeld, 2012). In 2050, the global demand for crop production is projected to increase by 100 to 110% (Tilman et al., 2011) and meat and milk demand will increase by 60% (Brian, 2015). Food demand will increase most in low-income countries due to

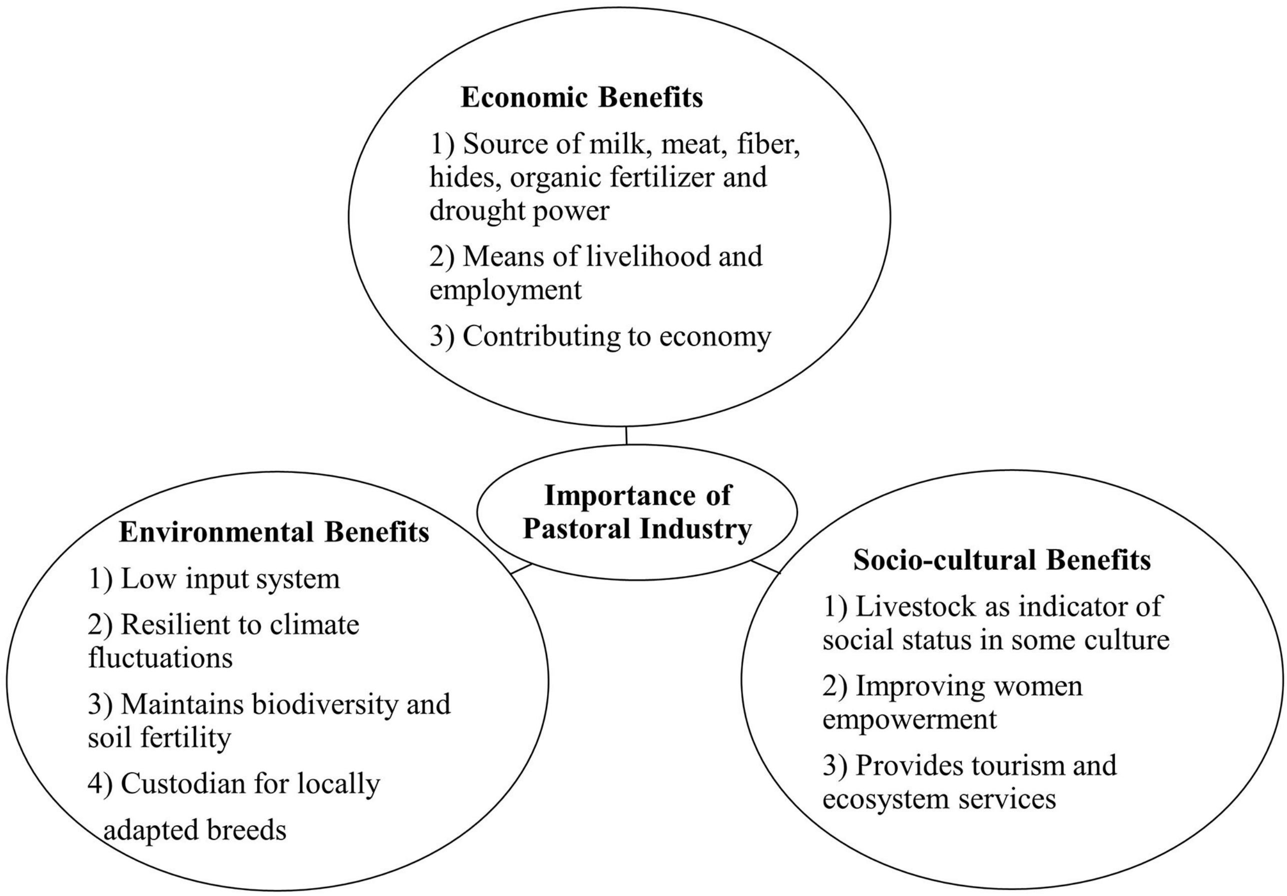

FIGURE 1 | Benefits of pastoralism (adapted from Blench, 2001; and Nyariki and Amwata, 2019).

increasing middle class and living standard (**Figure 2**). To meet increasing food demand, an additional 1 billion ha of land will be deforested with added agricultural GHG emissions of 3 Gt carbon dioxide equivalent (CO_2-e) per annum by 2050 (Tilman et al., 2011). The increased GHG emissions resulting in extreme climate events will negatively affect the pastoral industry by directly or indirectly affecting both crops and livestock production (IPCC, 2019).

Total anthropogenic GHG emissions are still increasing despite mitigation measures. In 2010, they reached 49 Gt CO_2-e comprising 76% CO_2, 16% methane (CH_4), 6.2% nitrous oxide (N_2O), and 2% fluorinated gases (IPCC, 2014). Combustion of fossil fuels and industrial processes are the main sources of CO_2, whereas agriculture is one of the main contributors to non-CO_2 GHG emissions. The IPCC (2019) special report outlines that increasing global GHG emissions increased land surface and ocean temperatures. The rise in land surface air temperature ranged from 1.38 to 1.68°C. Although rising temperatures could have stronger positive impact on biomass yields of C_4 than C_3 grass (Reeves et al., 2014), the impact of temperature on pastureland will depend on level of precipitation (Izaurralde et al., 2011). This warming climate has subsequently increased the frequency and intensity of drought in some regions and heavy precipitation in other regions. Increased air temperature along with decreased precipitation has amplified desertification in some areas such as Sub-Saharan Africa. Increased precipitation could

TABLE 1 | Forms of pastoralism (adapted from Blench, 2001).

Types	Definition
Nomadic	Pastoralists move with irregular patterns
Transhumance	Pastoralists move with regular back and forth pattern across locations
Pastoral farming/ranching	Practiced in ranches/pastures across high-income countries such as Australia, New Zealand, USA and developed regions of mid-income countries such as Argentina and Brazil
Agro-pastoralism	Pastoralists mostly depends on cultivation of crops for their livelihood and a small percentage of family income comes from livestock
Silvo-pastoralism	Integration of trees, forage and livestock grazing in a mutually beneficial way. Carbon sequestration is the most important environmental benefit of silvo-pastoralism, which utilize the principle of managed grazing

TABLE 2 | Geographical distribution of pastoral livestock species across continents (adapted from Blench, 2001).

Continental Region	Pastoral Animal Species
Central Asia	Horse
East and Central Asia	Bactrian Camels, Goat
South Asia	Camels, cattle, buffaloes, sheep, goats, ducks
West Asia	Donkey, Dromedaries and Goat
Highlands of Central Asia	Yaks
North Africa	Donkey, Dromedaries, Sheep and Goat
Sub-Saharan Africa	Cattle, Camel, Sheep and Goat
Europe	Sheep and Goat
Circumpolar Eurasia	Reindeer
Central America	Cattle and Sheep
North America	Cattle and Sheep
South America	Cattle and Sheep
Andes of South America	Llamas and Alpaca
Australia and New Zealand	Cattle and Sheep

increase productivity of pastureland, but drought could reduce both quantity and quality of pasture (Humphreys, 1991). Global warming will affect the distribution, abundance, and seasonality of plants and animal species. Warming climate has increased the likelihood of new disease outbreaks and infestations for plants, animals and humans. Several other consequences of global warming include flooding, melting ice, sea-level rise, wind and heat stress, which might have direct or indirect negative effects on plant and animal species. For instance, heat stress negatively effects the performance of pastoral livestock (Reyad et al., 2016), whereas flooding would make pastoral livestock systems more vulnerable mainly due to creating feed crisis and increasing morbidity and mortality of livestock (Hoffmann, 2010).

CLIMATE CHANGE AND PASTORAL INDUSTRY

The pastoral industry is having both negative and positive impacts on climate change and ecosystems, whereas climate change is also affecting the pastoral industry. This two-way interaction between climate change and the pastoral industry is summarized in **Figure 3**.

Impact of the Pastoral Industry on Climate Change

The livestock sector accounts for ∼19, 15, and 1.35% of global anthropogenic CH_4, N_2O, and CO_2 emissions (Rojas-Downing et al., 2017). Data about the impacts of the pastoral industry on climate change are not available. However, the intensity of the carbon footprint of livestock products is much greater for low input extensive systems than intensive production systems due to low productivity of animals in the former systems. For example, in 2015 the carbon footprint of milk production in Sub-Saharan Africa, South Asia, Western Europe and North America were 6.66, 4.10, 1.37, and 1.29 kg CO_2-e per kg fat and-protein corrected milk, respectively (FAO, 2018a). Thus, producing the same amount of milk from extensive system of Sub-Saharan Africa and South Asia would have much greater impact on climate change compared to the intensive systems of Western Europe and North America.

Among common food protein sources beef cattle have the largest GHG emissions and land use intensity (Swain et al., 2018), though that varies widely across production systems. For instance, the carbon footprint for beef production ranges from 12 to 129 kg CO_2-e per kg beef in extensive systems compared to 9 to 42 kg CO_2-e per kg beef in intensive systems (Nijdam et al., 2012). Similarly, land required to produce a kilogram of beef ranges from 286 to 420 m^2 in extensive systems and 15 to 29 m^2 in intensive systems (Nijdam et al., 2012). Specifically, intensive (grain-fed) beef systems require 45% less land and emit 30% less GHG than grass-fed beef systems to produce a kilogram beef (Capper, 2012). However, pastoral systems have the potential to increase soil organic carbon (SOC) stock over time, which is often overlooked due to the lack of data. A meta-analysis based on 42 long-duration studies (3 to 83 years, with an average of 18 years) showed that manure applied to soil had significantly greater SOC compared to soil without added manure or soil with chemical fertilizer applied (Maillard and Angers, 2014). Additionally, in pastoral systems, manure is naturally recycled back to land rather than managed in lagoons which produce substantial GHG in intensive systems (Aguirre-Villegas and Larson, 2017).

Increased food demand has increased livestock populations globally. For example, buffalo, cattle and goat populations have increased ∼2.2, 1.6, and 2.9 times between 1961 and 2016 (FAOSTAT, 2016). This increment in the livestock population has led to the expansion of pastureland by 20 and 33% in Asia and Latin America, respectively (FAOSTAT, 2017). Currently, 33.4 million km^2 of land used as grazing land (including pasturelands, rangelands, grasslands, savannas, shrublands and steppes) which cover ∼25% of the earth's surface (FAOSTAT, 2014). Grazing ruminant animals is one of the major drivers for pastureland expansion leading to deforestation particularly in the Brazilian Amazon as most of the deforested land ends up being used for cattle grazing (Barona et al., 2010; Schielein and Börner, 2018). Further increments in demand for animal source-food will reinforce pastureland expansion. Overgrazing by cattle can stimulate soil degradation and negatively affect freshwater and terrestrial ecosystems. Overgrazing resulting in reduction of vegetation cover is one of the major causes of soil erosion (Kairis et al., 2015). Overgrazing is a function of increasing stocking density. For example, stocking density increased from 1.3 to 1.7 animal units between 2003 and 2015 in the Brazilian Amazon region (Schielein and Börner, 2018). Blue water footprint for beef production in grain-fed system of United States is 2,034 L per kg carcass weight where more than 90% of the water is used for irrigation to produce feed (Rotz et al., 2019). However, properly managed grazing can enhance plant cover and soil health, which is discussed in the climate change adaptation section.

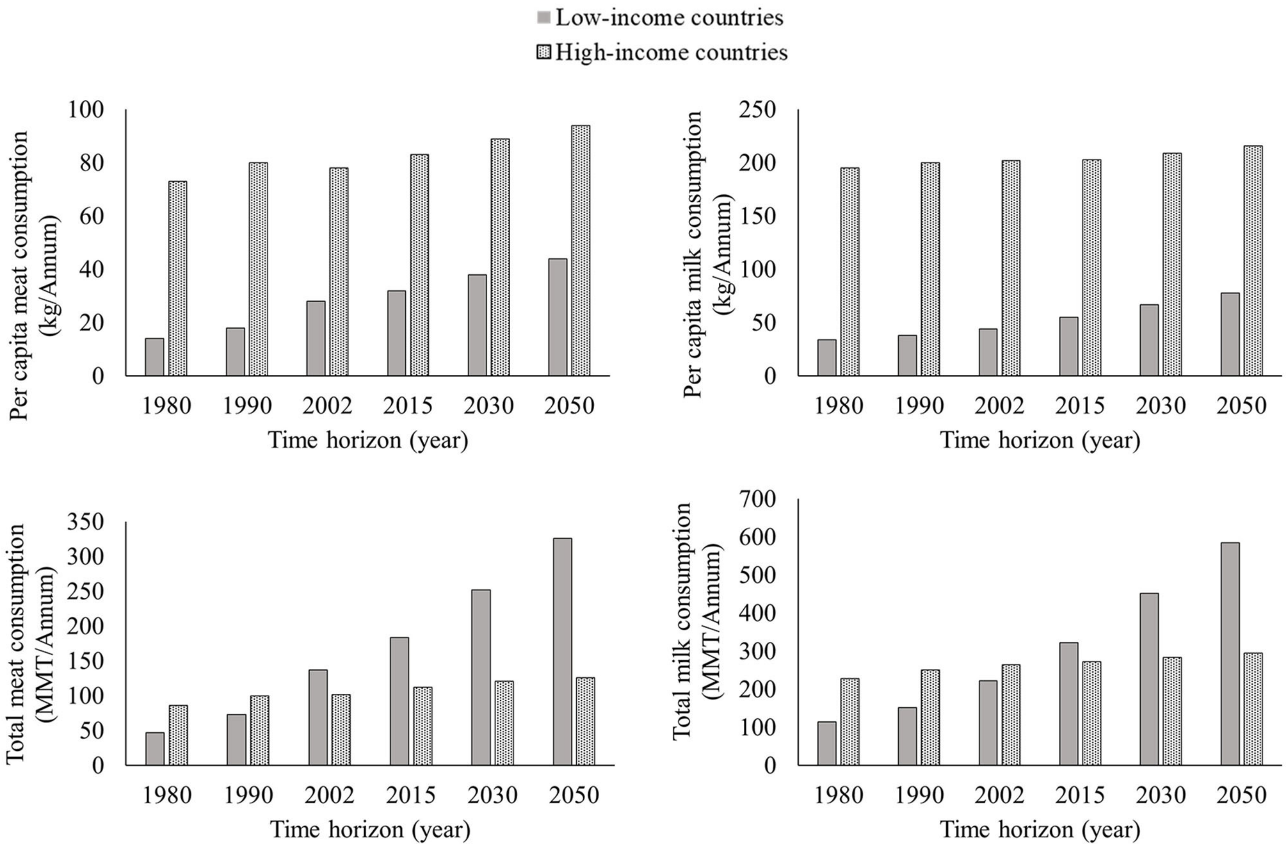

FIGURE 2 | Changing per capita and total milk and meat consumption overtime in developing and developed countries (adapted from FAO, 2006).

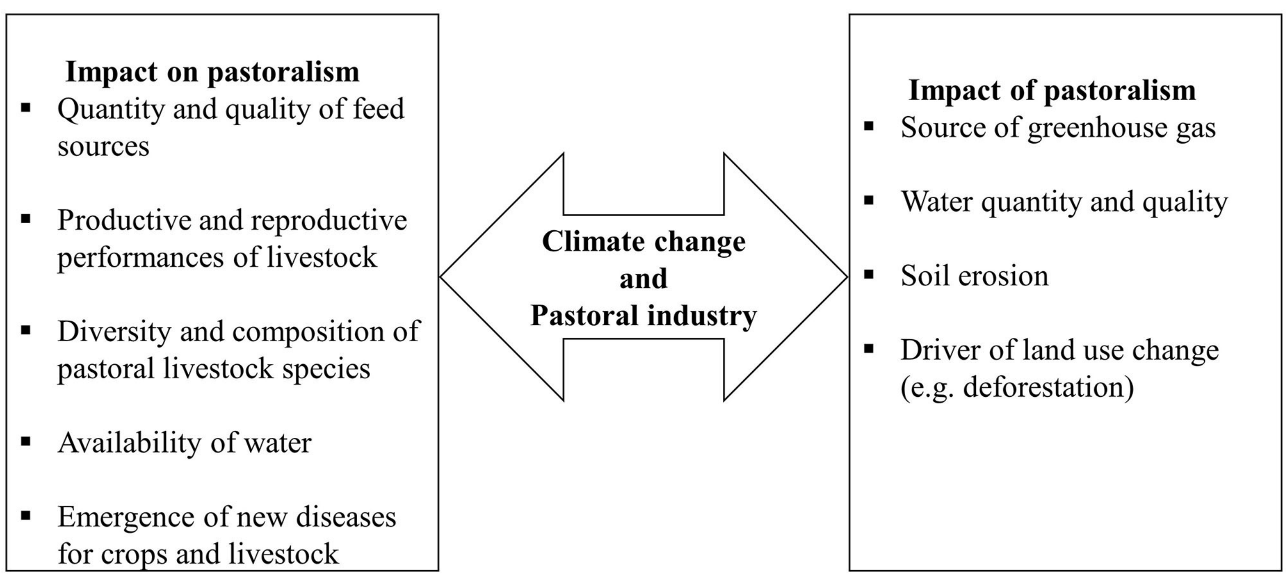

FIGURE 3 | Impact of food production and climate change on pastoralism and vice-versa (adapted from Thornton et al., 2009; Golub et al., 2013 and Sejian et al., 2018).

Impact of Climate Change on Pastoral Industry

Quality and Quantity of Forages and Pasture

A decline in biomass yield and fluctuations in biomass availability of pastureland determine the extent and magnitude of climate change risk for pastoral livestock production (Godde et al., 2020). Global scale projection between 2000 and 2050 shows that 74% of rangeland might experience a decline in biomass yield whereas 64 and 54% rangelands might experience inter-annual (year to year) and intra-annual (month to month) fluctuations of biomass availability, respectively. These changes might pose a serious threat to about 174 million ruminants particularly in the tropical region of Sahel, Australia, Mongolia, China and Uzbekistan (Godde et al., 2020). Additionally, pastures in tropical Australia and Sub-Saharan Africa are poor in quality (e.g., low protein content and low digestibility), mainly during the dry season, due to poor soil nutrient profiles, which might be worsened with frequent and longer droughts (Humphreys, 1991).

Furthermore, a shift from herbaceous pasture to shrubs and trees is projected to happen on 51% of rangeland areas globally (Godde et al., 2020). This shift from herbs to shrubs and trees has important implications for pastoral production systems because herders need to couple livestock species with vegetation changes. For example, woody pastureland would be suitable for goats but not as suitable for cattle or sheep.

Elevated CO_2, rising temperature and reduced precipitation could affect growth of forage species (**Table 3**). Increased CO_2 and precipitation will increase net primary production of rangeland and pastureland species, but the impact of temperature rise on net primary production is uncertain due mainly to the uncertainty of predicting precipitation (Izaurralde et al., 2011). Impacts of climate change also depend on the metabolic pathways (e.g., C_3 vs. C_4) of pastureland grass species. For example, rising temperatures would have the greatest positive effect on the growth of warm season C_4 grass whereas rise in CO_2 concentrations would mainly affect cool season C_3 grass (Reeves et al., 2014). In some regions (e.g., East and West Africa), increased population and land competition led people to covert pastureland into cropland, which reduced communal pastureland (Godde et al., 2020). Feeding crop residues could be a way to cope with this land competition.

Weed species showed a relatively strong response to elevated CO_2 which could enhance growth and make them herbicide resistant (Ziska, 2003). This will increase competition between weed and crops resulting in greater loss of crop production. Competition will be exacerbated by rising temperatures because growth of most weeds (mostly C_4 metabolic pathway) will be stimulated (Ramesh et al., 2017). Patterson et al. (1979) showed that a 3°C increase in temperature could potentially increase the biomass yield of itchgrass by 80%. Some weed species such as cheatgrass and yellow star thistle can grow faster with reduced precipitation due to their adaptability to drought (Hatfield et al., 2011). Weed infestation and growth also depend on crop species, therefore, all combinations of weed and crops (or forage) interactions (e.g., C_3 weed and crop, C_4 weed and crop, C_4 weed and C_3 crop and any other combinations) need to be examined (Ramesh et al., 2017).

TABLE 3 | Impact of climate change on photosynthesis and growth of different forage species.

Forage species	Metabolic pathway	Impact of climate change			References
		Elevated atmospheric CO_2	Increased Temperature	Drought/ Decreased Precipitation	
Rhizoma peanut	C_3	+	+	NA	Newman et al., 2001
Ryegrass	C_3	+	NA	NA	Suter et al., 2001
Alfalfa	C_3	NA	NA	–	Thomson et al., 2005
Tama	C_3	+	NA	NA	Greer et al., 1995
Matua	C_3	+	NA	NA	Greer et al., 1995
Nui	C_3	+	NA	NA	Greer et al., 1995
Maru	C_3	+	NA	NA	Greer et al., 1995
Suckling clover	C_3	+	NA	NA	Greer et al., 1995
Tallarook	C_3	+	NA	NA	Greer et al., 1995
Bentgrass	C_3	+	NA	NA	Greer et al., 1995
Kara	C_3	+	NA	NA	Greer et al., 1995
Roa	C_3	+	NA	NA	Greer et al., 1995
Puna	C_3	+	NA	NA	Greer et al., 1995
Huia	C_3	+	NA	NA	Greer et al., 1995
Crabgrass	C_4	NC	NA	NA	Greer et al., 1995
Raki	C_4	NC	NA	NA	Greer et al., 1995
Bahiagrass	C_4	NC	+	NA	Newman et al., 2001

"+": Positive impact on growth, "–": Negative impact on growth, NC, No change; NA, Not Applicable or No data available.

Plant pests (insect and disease) cause major losses in crop yields, which could be aggravated by climate change. Foodtank (2019) summarized the potential impact of pests on crop yield losses under changing climate. Pests could reduce crop yields annually by 20 to 40% (Flood, 2010). Global crop yield losses will further increase between 10 and 25% for each degree of global surface temperature increase. Rising temperatures may affect distribution, severity of infestation and life cycles of cold-blooded pest species or they may reduce resistance of crop or forage species to disease. Climate change could create extremely severe food insecurity. For example, wheat blast caused by a fungus (Magnaporthe oryzae), a recently emerged wheat disease, poses a threat to tropical South America and South Asia. The disease affected approximately 3 million hectares of wheat field in 1990 [International Maize and Wheat Improvement Center (CIMMYT), 2019]. Recently, the disease has spread in South Asia causing 51% yield reduction in infected areas (CIMMYT, 2019). This fungus has the ability to infect other grass species such as barley and rice. Furthermore, climate change might increase the vulnerability of crops susceptible to the disease or newly emerged diseases due to reduced disease resistance of host crop species.

In addition to forage growth and distribution, climate change will also affect forage quality. A meta-analysis by Dumont et al. (2015) showed that elevated CO_2 increased non-structural carbohydrates by 25% but decreased nitrogen content by 8%. However, the increased abundance of legume species with increasing CO_2 might compensate for the reduction in nitrogen. The impact of temperature rise on forage chemical composition or digestibility was inconsistent, and while drought increased digestibility, variability among studies was high.

Diversity and Composition of Pastoral Livestock Species

Pastoral systems utilize and maintain livestock diversity to cope with climatic variability and keep production costs as low as possible (Kaufmann et al., 2016). Locally adapted livestock breeds are reared in pastoral systems because local breeds have greater fit with the local climatic conditions than exotic breeds (Provenza, 2008). Pastoralists use various livestock species determined mainly by their geographic location and climatic conditions as discussed earlier (**Table 2**). However, Hoffmann (2010) concluded that climate change will affect diversity of pastoral livestock in two ways. First, direct effect of rising temperature (e.g., heat stress) or extreme weather events (e.g., flood or storm) will increase the risk of morbidity and mortality of locally adapted breeds compared to exotic breeds because exotic breeds in the high-output intensive systems are well-protected from climatic adversaries due to better housing and management than local breeds in the grazing systems. Second, increasing food demand and climate change will push low input and extensive production systems to improve efficiency and reduce their environmental footprints. This intensification will remove most locally adapted livestock species or breed, which will not be cost-effective in high input systems.

Productive and Reproductive Performance of Livestock

The impacts of climate change will not be limited to crop production, but will also affect efficiency, product quality, production, and reproduction of livestock species. Heat stress, for example could cause huge economic losses in the dairy and beef industries. Severity of heat stress is lower in beef cattle than dairy cattle due to lower metabolic rate and heat production resulting in higher temperature-humidity index in beef cattle than dairy cattle (St-Pierre et al., 2003). Heat stress can reduce up to 25% of daily milk yield along with reduced feed intake when dairy cows are exposed to high temperature and humidity (Cowley et al., 2015; Summer et al., 2019). Reductions in feed intake can be used as an indication of heat stress. Intake reductions start at 25°C with 20 to 40% intake reductions when temperatures exceed 40°C (Hahn, 1999). Heat stress could reduce milk production by 19% under extensive tropical production systems, which have comparable levels of milk production to pastoral systems (Reyad et al., 2016). In terms of milk quality, Cowley et al. (2015) reported a decrease in milk protein content due to heat stress. The effect of heat stress on milk lactose content is not yet clear as some studies report a decrease, but others report no change (Summer et al., 2019). Heat stress in beef cattle causes high mortality and affects animal behavior such as increased respiration rate, decreased rumination and feed intake, and increased frequency of drinking water (Summer et al., 2019). Morignat et al. (2015) reported that each degree temperature increase above a certain threshold is associated with a 5% increase in mortality risk. Heat stress adversely affects follicle development and reduces pregnancy rate in cattle (Liu et al., 2019). An increase in temperature-humidity index from 72 to 78 reduced pregnancy rate from 39.4 to 31.6% in dairy cows (Domínguez et al., 2005). Nonetheless, the impact of heat stress depends on livestock species or breed or type. For example, tropical cattle breeds are more adaptive to heat stress than temperate breeds. At a similar level of heat stress exposure, tropical cattle had relatively less reduction of feed intake (25 vs. 30%), average daily gain (12 vs. 18%) and daily milk yield (20 vs. 28%) than temperate cattle (Johnson, 2018). This difference in heat stress tolerance between cattle breeds is paramount to select breed with greater adaptive capacity, which will be further discussed in adaptation section.

Water Scarcity

Overall, the agriculture sector consumes about 70% of total freshwater making this sector the largest user of freshwater (Thornton et al., 2009; IPCC, 2019). Although the livestock sector accounts for 8% of human water use globally (Nardone et al., 2010), pastoral systems mostly depends on rainfall with minimal consumption of ground and surface water compared with intensive livestock production systems. Water is essential for livestock production because water is used for drinking, and to produce feed and process products. Approximately 90% of water consumption in the livestock sector is associated with feed production (FAO, 2018b). Thus, increasing livestock populations to meet global food demand will increase water consumption significantly. In general, ruminants drink 3.5 to 5.5 L of water/kg dry matter intake depending on physiological status of the animal, feed water content and local climatic conditions. Increasing temperature will further increase drinking water consumption by 2- to 3-fold (Nardone et al., 2010). Water unavailability or contamination can affect livestock production and reproduction (Rojas-Downing et al., 2017). For example, contamination of freshwater with saline water due to sea level rise could affect metabolism and fertility of animals (Nardone et al., 2010). Dehydration or water deprivation increases body and rectal temperature but reduces respiration rate in small ruminants. However, respiration rate might be increased due to dehydration with rising environmental temperature. Water

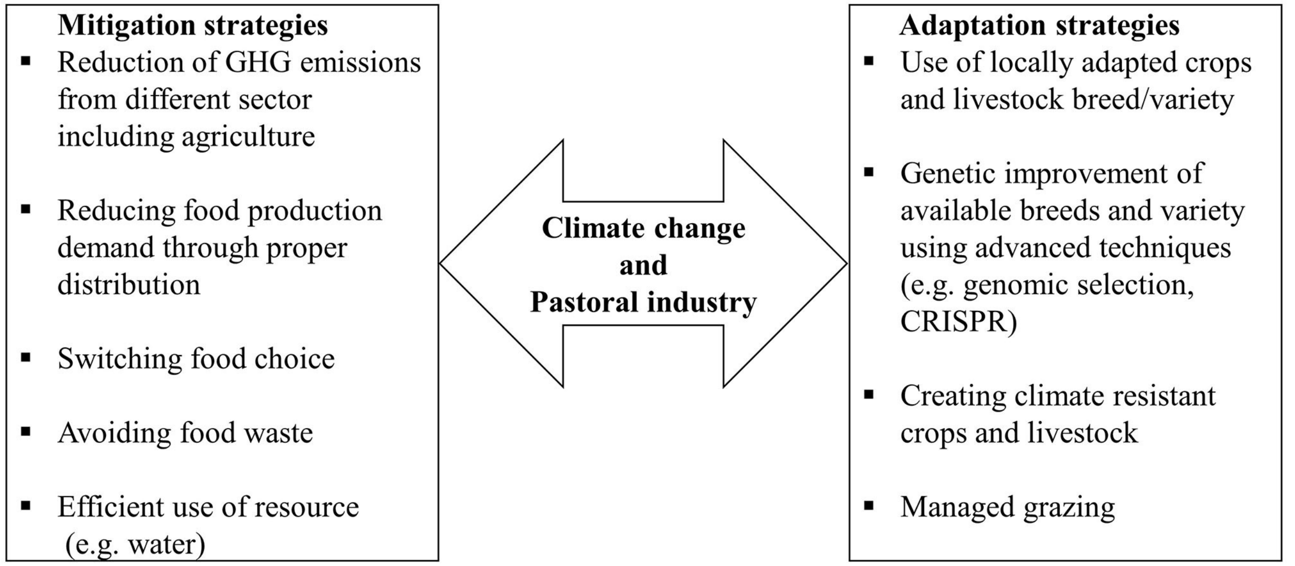

FIGURE 4 | Potential climate change mitigation and adaptation strategies for pastoral industry.

deprivation leads to body weight loss due mainly to reduced feed intake, which can be up to 60% in small ruminants. Between 25 and 50% water restriction reduced milk yields by 18 to 20% in small ruminants (Akinmoladun et al., 2019).

Emergence of New Diseases for Livestock

Climate change poses a threat to human and animal health due to either increasing severity or frequency of outbreaks for known diseases or emergence of new diseases. Rising temperature or increasing severity and frequency of extreme events could also affect animal health either directly or indirectly (Nardone et al., 2010; Bett et al., 2017). Rising temperature increases disease susceptibility and mortality of animals by suppressing immunity of host animals or favoring pathogens. Indirect effects of climate change on disease are associated with ecosystem changes or socio-cultural changes such as changes in life-style, which might increase vector-pathogen-host contact. Rising temperature has already changed parasitic disease occurrence by helminth (seasonality, abundance and spatial variation of spread) (Van Dijk et al., 2010). Climate change could affect animal health by affecting either vector or pathogens or host. Pathogens for anthrax, black quarter and helminths, which complete part of their life cycle outside a host, could be stimulated with temperature rise (Bett et al., 2017). For instance, growth of *Bacillus anthracis* spores (pathogen for anthrax) depend on temperature, humidity and nutrient availability of the environment (WHO, 2008). There is a lack of data on indirect effects of climate change on diseases (Bett et al., 2017). Furthermore, the association between climate change and disease occurrence is complex and further studies are required to unravel confounding between climate change parameters and other factors causing a disease. The potential and currently available climate change mitigation and adaptation strategies are discussed in the following two sections (**Figure 4**).

CLIMATE CHANGE MITIGATION STRATEGIES

Mitigation of climate change aims to either reduce sources of GHG emissions or increase sinks of GHG (IPCC, 2014). Mitigation of emissions from the agricultural sector can be achieved either through reducing emissions per unit of food product or per unit of land (supply-side approach) or through reducing food demand, switching food choice, reducing avoidable food waste and improving access to food through proper distribution (demand-side approach) (IPCC, 2014).

Major emission sources for livestock products are enteric CH_4, N_2O, and CH_4 from manure management during storage and after cropland-application, and CO_2 and N_2O emissions from feed production and transportation. Enteric emissions from ruminants could be reduced through: (1) nutritional manipulation (e.g., improving feed digestibility, replacing structural carbohydrates with non-structural carbohydrates in the diet) (Hristov et al., 2015); (2) supplementation of feed additives (e.g., feeding 3-nitrooxypropanol and red algae have great potential to reduce enteric emissions) (Roque et al., 2019); (3) genetic improvement (e.g., direct or indirect genetic selection for enteric CH_4 reduction using advance technique such as genomic selection), and (4) improved herd management and fertility (Knapp et al., 2014). The enteric emission mitigation strategies might not be equally applicable and relevant for all pastoral production systems. For example, supplementation of concentrate feeds (i.e., source of non-structural carbohydrates) has great potential to reduce enteric CH_4 either through improving production performance (i.e., dilution effect) or through acting as a sink of hydrogen in the rumen (Wattiaux et al., 2019). This strategy could be implemented in agro-pastoral systems. However, improving digestibility of natural pasture is challenging, but can be achieved to some degree through grazing management that helps to prevent maturation of plant species (see climate change adaptation strategies section below). Feed additives might be a challenge if they need to be given to animals on a daily basis. However, technologies can be developed in which feed additives can be given in a slow release form covering several days or weeks. Breeding programs focusing on improving productivity, fertility and adaptability of cattle in the pastoral system could also be implemented.

Reducing duration of manure storage, solid-liquid separation and anaerobic digestion are potential strategies to reduce emissions from manure storage, whereas feed production related emissions could be reduced by altering the amount and improving the timing and application of chemical fertilizer and manure to crop-fields (Aguirre-Villegas and Larson, 2017; Wattiaux et al., 2019). Most of these techniques are not necessary for pastoral systems because manure is recycled naturally.

A recent study showed that environmental impact of producing the same product can vary by 50-fold among producers (Poore and Nemecek, 2018). This variation among producers provides the potential to reduce environmental impact of food products by improving efficiency (e.g., feed efficiency for livestock production, crop yield per unit of N fertilizer) and by adopting best management practices (Clark and Tilman, 2017). Based on life cycle analysis, the carbon footprint for feedlot beef was much lower compared to grass-fed beef (6.0 vs. 9.6 kg CO_2-e per kg carcass weight) due to greater productivity of feedlot beef production (Stanley et al., 2018). However, this comparison did not take into account SOC change. When SOC change was taken into account the carbon footprint for feedlot beef was greater than grass-fed beef (6.1 vs. −6.6 kg CO_2-e per kg carcass weight) due to carbon sequestration in grass-fed beef systems (Stanley et al., 2018). Although pastoral management systems cannot be fully compared with grass-fed beef system it is important to evaluate these systems by taking into account all components within the system including accounting for SOC change and carbon sequestration.

Dietary choices can impact GHG emissions due to wide differences in emission intensity among food sources. For instance, the carbon footprint of ruminant meat is 3 to 10 times greater than other animal-source foods such as milk, dairy products, chicken, and 20 to 200 times greater than plant-based foods such as cereals and pulses (Clark and Tilman, 2017). Thus, diets composed of plant-based food could potentially reduce food production related GHG emissions by up to 50% (Poore and Nemecek, 2018). When the impacts of global population growth are combined with income-dependent dietary changes, the net effect would be 80% increase in food production related GHG emissions by 2050 compared to dietary trend of 2009, however, food production emissions would show no net increase if by 2050 the global diet became an average of the Vegetarian (combination of fruits, vegetables, grains, sugars, oils, eggs, and dairy with a single monthly serving of meat or seafood), Pescetarian (vegetarian plus seafood) and Mediterranean (Pescetarian plus modest amount of poultry, pork, lamb and beef) diets (Tilman and Clark, 2014). While diets composed of processed foods containing high sugars, fats and carbohydrates might help to reduce GHG emissions, they will not improve human health (Tilman and Clark, 2014). Myriad of factors, including acquired cultural preferences, accessibility, price, and nutritional needs and knowledge of consumers, influence people's dietary choices (Tilman and Clark, 2014). Therefore, dietary solution should consider the cultural and physical environments in tandem with human health. Any comparisons between animal- and plant-source foods also needs to consider the nutritional value of the products relative to the needs of the consumer. For instance, the environmental footprint of most animal- and plant-source foods are similar when comparisons account for the higher biological value of animal proteins (Tessari et al., 2016). Furthermore, livestock products produced under managed grazing systems have the potential to improve soil health, increase carbon sequestration and reduce water pollution (Derner and Schuman, 2007; Eisler et al., 2014; Teague et al., 2016; Stanley et al., 2018).

Supply chain (harvest to consumption) food loss including food waste accounts for roughly 30 to 40% of food loss (Godfray et al., 2010). The extent of food losses is almost the same between high, mid and low-income countries. However, in low-income countries most losses happen on-farm due to poor storage, distribution, conservation and processing whereas in high-income countries most food losses happen at the consumer level due to food waste (Godfray et al., 2010). Most food losses are avoidable, however, some losses cannot be avoided, such as those from peeling some fruits and vegetables. Avoiding food loss can have profound impact on GHG reductions from food production. Life cycle analysis conducted in the United States showed that the carbon footprint of milk can be reduced by 23% through avoiding 12% milk loss at retail or an additional 20% loss at consumer levels due to cooking loss, spoilage and waste (Thoma et al., 2013).

Although water scarcity is a regional issue, it needs to be addressed to meet the future water demand, which is expected to increase by 50% (UNEP, 2008). Increasing human populations along with increased water use by the industrial and agricultural sectors will further expand water scarcity even in places with high rainfall (Doreau et al., 2012). Although water footprint for the same livestock product varies widely across production systems, livestock-induced water scarcity can be avoided by reducing blue water use (surface plus ground water) (Doreau et al., 2012). Crop-livestock integration (i.e., feeding crop by-products to livestock) has been proposed as a potential management practice to reduce water use for livestock production through water recycling (van Breugel et al., 2010; Lal, 2020). Improved irrigation management (e.g., timing and optimizing irrigation through advanced precision technology), using crops which require less water (e.g., triticale and sorghum require less irrigation compared to alfalfa and corn), purchasing feed ingredients from areas where irrigation is not required, and breeding crops to increase either biomass yield or drought adaptability are some of the strategies to reduce water consumption for livestock products.

CLIMATE CHANGE ADAPTATION STRATEGIES

The pastoral industry has been using indigenous plants and livestock breed/variety/species, which are known to be most adapted to specific regional climatic conditions and exposure of other challengers such as disease outbreak, heat stress, parasite or pest infestation (Provenza, 2008). Local zebu cattle, for example, have greater heat tolerance and disease resistance in tropical climatic conditions than exotic temperate cattle (Johnson, 2018). However, livestock with greater disease resistance and heat tolerance only may not sustain livelihoods due to their low productivity and poor fertility. Thus, breeding strategies have focused on multi-trait selection aiming to create a climate-smart or climate-adapted livestock breed or variety along with improved reproductive and productive efficiency resulting in lower emission intensity. Similarly, plant breeding needs to improve forage and crop varieties that are drought tolerant, resistant to pest infestations and plant diseases, with greater yield and ability to compete with weed infestations. Traditional breeding strategies that utilize natural variation might not always be useful or might take longer to create climate smart livestock and crops. Modern breeding and selection techniques such as genomic selection could make the improvement quicker by reducing generation intervals and allowing traits with low heritability (e.g., fertility traits in cattle) to be included in the breeding scheme. New techniques such as CRISPR genome editing could make much faster progress in livestock and crop varieties that are adapted to ever changing climate to ensure the sustenance of the pastoral industry (Derazmahalleh et al., 2019). However, choice of breeding approaches will depend on multiple factors such as phenotypic and genotypic information, type of traits (simple or polygenic) and regulations in the regions or countries.

Managed and adaptive multi-paddock grazing based beef system can be a potential sink for carbon rather than a source of carbon emissions due to sequestration (Stanley et al., 2018). Although grazing can stimulate soil erosion, lightly grazed grassland can potentially reduce soil erosion by about 60% compared to cropland (Yu et al., 2019). The impacts of grazing on soil erosion and SOC stock depend on regional climatic condition (e.g., dry warm vs. dry cool, moist warm vs. moist cool), grassland vegetation type (e.g., C_3 or C_4 or mixed), and how grazing is managed (Abdalla et al., 2018). For instance, cover crops can reduce soil erosion substantially (Teague et al., 2016). High grazing intensity has greater impact on SOC increment in C_4- than C_3-grassland (Abdalla et al., 2018). As an additional benefit, winter grazing can reduce risk and intensity of wildfire in shrub-grassland areas relative to un-grazed areas through reducing fuel load for wildfire (Davies et al., 2016).

Several other forms of regenerative production systems namely silvopastoral, intercropping and conservation agricultural systems also have great potential to sequester carbon (Provenza et al., 2019). Silvopastoral systems, for example, can enhance soil carbon restoration five times greater than managed grazing and are resilient against abrupt climatic events (e.g., rising temperature, drought) due to presence of grasses, shrubs, and trees (Dass et al., 2018). Saponins and tannins commonly found in forbs, shrubs and tree leaves can reduce CH_4 and N_2O emissions from ruminant production systems which is an additional benefit of silvopastoral system (Hristov et al., 2013). In addition to GHG mitigations, co-benefits of managed grazing and regenerative agriculture include enhancement of soil health, biodiversity, water holding capacity of soil and ecosystem services (Teague et al., 2016; Provenza et al., 2019).

Provenza (2008) mentioned the following strategies to improve grazing: (1) coupling animal needs with forage availability, (2) selecting animals that are adapted to local conditions and landscapes, and (3) creating grazing systems that simultaneously benefit soils, plants, herbivores and human beings. Grazing management should also focus drought and weeds, two serious threats to pastures. Drought can be managed by carefully managing grazing, reducing carrying capacity of pasture to 75% less than in normal years, and slowing grazing rotations (Rinehart, 2008). Weeds can be managed by multispecies and high-density rotational grazing (Rinehart, 2008). Increased grazing duration can be more damaging than higher stocking density which can help to avoid palatability issue and weed problem in pastures (Rinehart, 2008).

Finally, integrating scientific knowledge gathered by researchers with the experiences acquired by the herders would help to manage grazing in better ways through: (1) improving animal training to utilize pasture properly, (2) maintaining grazing boundaries, (3) altering temporary forage palatability scoring made by grazing animals, and (4) stimulating animal appetite and intake by manipulating meal sequence (Meuret and Provenza, 2015; Molnár et al., 2020). For example, skilled herders in France design grazing circuits at a meal scale to increase appetite and intake, to create synergies among meal phases, and to increase intake of abundant but less palatable forages (Meuret and Provenza, 2015). To do so, they partition landscapes into grazing sectors that are carefully sequenced within daily circuits. Meals are based on complementarity blends of terrain and plant communities within and among sectors, not on particular plants. To do so, herders identify and ration various sectors into phases of a meal: appetite stimulator or moderator, first course, booster, second course, and dessert sectors.

CONCLUSIONS

Climate change and increased food demand pose a serious threat to the pastoral industry, which has considerable economic, ecological, and socio-cultural importance. Further population growth will aggravate the impact of climate change on the pastoral industry. Climate change is affecting the pastoral industry through feed and fodder production, productivity and fertility of livestock, pest and disease outbreak for crops and livestock, water scarcity for livestock and feed production. The pastoral industry also impacts climate change negatively through emissions of GHG, expansion of pastureland through deforestation, erosion and degradation of soil, and air and water quality. Both supply-side (e.g., reducing emission intensity and improving resource-use efficiency) and demand-side (e.g., reducing food demand and food waste, and improving food access through proper distribution) mitigation strategies are needed to reduce emissions. In addition to properly managing animals and pastures, modern breeding and selection techniques, such as genomic selection, CRISPR genome-editing tools, should also be used to aid crop and livestock adaptation to ever changing climate, thus ensuring sustainability of the pastoral industry.

AUTHOR CONTRIBUTIONS

MEU participated in all components of the review, conception and design, and major contribution in writing the manuscript. EK participated in drafting and writing the manuscript. All authors read and approved the final manuscript. All authors contributed to the article and approved the submitted version.

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REVIEW
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Animal Welfare in Extensive Production Systems Is Still an Area of Concern

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Traditionally, research on farm animal welfare has mainly been focused on welfare problems thought to be common in intensive systems, whereas the welfare of animals kept in extensive systems has attracted much less attention. This may be due to the generally held belief that extensive systems are advantageous in terms of animal welfare. Although it is undeniable that extensive systems have many benefits in terms of animal welfare, they are by no means free of welfare problems. This review highlights the animal welfare problems that are most likely to be found in extensive systems following the four animal welfare domains of "nutrition," "environment," "health," and "behavior." Extensive environments are highly variable and heterogeneous in terms of climate conditions, food quality, and access to high-quality water, and this can raise serious welfare concerns related to chronic hunger and thirst, and thermal stress. These problems will vary depending on the location and time of year. Some diseases are more likely in extensive systems than in intensive ones and this can be compounded by supervision of animals being more difficult in extensive systems. Several painful husbandry procedures as well as neonatal mortality and predation are other potential welfare issues for animals raised in extensive systems. Finally, infrequent handling and / or potentially aversive handling can impair human-animal relationship and have a negative effect on the welfare of extensive livestock. Detection and monitoring of welfare problems in extensive systems are essential for implementing practical solutions adapted to local challenges. Selecting animals that are adapted to local conditions reduces some of the welfare problems encountered in extensive systems. Practice-led innovations should be undertaken in extensive systems and should support knowledge-exchange strategies with producers.

Keywords: animal welfare, extensive livestock, knowledge exchange, nutrition, environment, health, behavior

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INTRODUCTION

Animal welfare is an essential element of modern animal production. First and foremost, animal welfare is grounded on ethical concerns that derive from the fact that animals are sentient beings, i.e., able to suffer and experience emotions (Le Neindre et al., 2017).

Societal concern over the welfare of farm animals has increased recently and a growing number of citizens in many countries now demand that farm animals are reared, transported, and slaughtered as humanely as possible. For example, according to a survey done in 2015 and involving more than 27,000 citizens from the 28 Member States of the European Union, 94% of EU citizens think that it is important to protect the welfare of farm animals. Interestingly, this percentage ranged from 86 to 99%, showing that even in the EU countries that are supposedly less concerned about the welfare of animals, a clear majority of citizens believe that it should be protected (European Commission, 2016).

Improving animal welfare may have additional benefits. As many welfare problems have a detrimental effect on production, improving the welfare of farm animals very often has positive effects on performance. Also, improving animal welfare is one of the strategies that may contribute to reduce the use of antimicrobials in farm animals (EMA EFSA, 2017) and hence may have long-term benefits for human health.

Traditionally, research on farm animal welfare has mainly been focused on welfare problems that are thought to be common in intensive systems. Conversely, welfare of animals kept in extensive systems has attracted much less attention. However, extensive systems of animal production are very important in many parts of the world. Extensive pastoralism occurs on 25% of global land surface and supports around 200 million subsistence pastoral households (Nori et al., 2005). In Africa, 40% of the land is dedicated to pastoralism (IRIN., 2007).

Despite two recent reviews on the welfare of extensively kept livestock, publications on this topic are limited (Villalba and Manteca, 2016; Villalba et al., 2016). The scarcity of research on animal welfare in extensive systems is partly due to the generally held belief that extensive systems are advantageous in terms of animal welfare. Admittedly, conditions experienced in extensive situations are more likely to provide for the behavioral needs of animals (Hemsworth et al., 1995). Indeed, extensive management systems are based on providing a natural environment where animals can express natural behaviors such as grazing or exploration. Also, livestock animals can exercise, which may be beneficial for their health (Regula et al., 2004). Pastures may provide a more comfortable lying area compared to indoor housing systems (e.g., dairy cattle, Krohn and Munksgaard, 1993) and may prevent the incidence of some diseases such as mastitis in dairy animals (Washburn et al., 2002).

However, the possibility to display natural behavior can be constrained by environmental features. For example, cows may prefer not to graze if temperatures are too high. Legrand et al. (2009) reported that lactating Holstein cows preferred pasture only at night and preferred indoor housing during the day, especially when the temperature and humidity increased, under the housing and environmental conditions tested. Charlton et al. (2011) also reported that lactating Holstein cows exhibited a partial preference to be indoors, which was influenced by rainfall and milk yield. Those studies on preference testing and motivations show that, in some conditions, animals may perceive outdoor conditions as aversive and if given the choice they would prefer the protection from the indoor area.

In principle, the welfare of herbivores kept in extensive grazing systems should benefit from the fact that they have evolved to make the best use of such environments. However, as commented by Villalba et al. (2016), animals are not always kept where they evolved, and the unpredictability of environmental factors, coupled with the management of livestock by humans, does not always match the adaptive features of livestock, which can lead to welfare problems for livestock kept in extensive systems. In fact, livestock that live under extensive conditions are partially under the care of humans and, on the other hand, they fend for themselves for part or most of their lives. Therefore, selecting for animals adapted to prevailing local conditions contributes to avoid or reduce many of the welfare issues that will be discussed later (Provenza, 2008).

Despite these constrains, it remains true that extensive systems offer several advantages over intensive ones from an animal welfare standpoint, mainly in the behavioral domain. On the other hand, however, it is also true that extensive systems may pose several welfare problems that are far less common or severe in intensive systems.

The objective of this paper is to discuss animal welfare problems in extensive systems and suggest improvement strategies, as well as areas deserving further research. Several welfare issues included in this review are found in intensive systems also, but they still pose a significant threat to the welfare of animals in extensive systems, where they may require improvement strategies different from those commonly used in intensive systems.

As most of the extensive livestock are herbivores, particularly ruminants, this review will mainly focus on ruminants -mostly cattle, sheep and goats-, but pigs kept under extensive conditions will also be considered when appropriate. When there is little or no published information of a particular welfare issue in domestic livestock, references to studies on wild ungulates will be included. Welfare problems during transport and at slaughter will not be considered. To provide a conceptual framework for our discussion, first we will briefly summarize the concept of animal welfare.

WHAT IS ANIMAL WELFARE?

The concept of animal welfare can be approached from different perspectives and these have been grouped into three categories: biological functioning, emotional state and "naturalness" (Fraser et al., 1997). Each of these approaches has its own merits but none of them captures on its own the different aspects of animal welfare. It has been suggested, therefore, that the assessment of animal welfare must include all three approaches. It is widely accepted that animal welfare encompasses not only the physical health of the animals (i.e., the absence of diseases and injuries) but also their behavior and emotions (Duncan and Fraser, 1997; Mendl, 2001).

The welfare of an animal can be measured objectively and independently of moral considerations, and may range from very poor to very good. According to one of the most widely accepted scientific definitions of animal welfare, the welfare of an individual is its state as regards its attempts to cope with its environment (Broom, 1986). An in-depth discussion of this definition is well-beyond the scope of this paper and it suffices to say that welfare depends on whether the animal is able to cope and on how much it has to do to cope with environmental challenges. As feelings are part of the coping mechanisms used by animals, feelings are an important part of welfare.

For many years, the Five Freedoms (Farm Animal Welfare Council, 1992) have provided a useful framework to identify the welfare problems of farm animals. These freedoms, which represent ideal states rather than actual standards for animal welfare are (1) freedom from thirst, hunger and malnutrition, (2) freedom form thermal and physical discomfort, (3) freedom from pain, injury and disease, (4) freedom to express most patterns of normal behavior, and (5) freedom from fear and distress.

More recently, the Five Freedoms have been criticized on the grounds that they can be misunderstood as aiming at eliminating all negative experiences (which is not realistic or even desirable) but also because they fail to capture our current understanding of the biological processes underlying animal welfare (Mellor, 2016). As an alternative to the Five Freedoms, the so-called Five Domains Model for assessing animal welfare was developed to address these problems. The Model incorporates four physical domains of "nutrition," "environment," "health," and "behavior," and a fifth "mental" domain. Each physical domain has an impact on the affective state of the animal (i.e., on the fifth domain), and the net outcome in the mental domain resulting from the combination of the four physical domains represents the animals' overall welfare state.

NUTRITION AND FOOD SELECTION

Chronic Hunger

In extensive systems, animals forage for most of their feed and must sometimes cope with long periods where available food does not have sufficient nutrients to meet their requirements. When this is the case, animals will lose body condition and suffer chronic hunger. For example, in a study conducted on family farms from Southern Brazil, a mean prevalence of 14% of extensive dairy cows showed low body condition scores suggesting low pasture quality and availability on some farms (Costa et al., 2013).

Very low body condition may compromise the immune function of animals and very low body condition scores increase the risk of health problems during lactation in dairy cattle (Roche et al., 2008). Moreover, underfeeding is likely to have direct, negative effects on the affective state of the animals.

In addition to macronutrients, levels of minerals and vitamins may be inadequate. In extreme cases, deficiencies can result in death. For example, when raised on phosphorus-deficient pastures, cattle seek out bones to chew which can result in death from botulism in unvaccinated cattle, as decaying carcasses favor the concentration of botulinum toxin (McCosker and Winks, 1994).

Ruminants try to adapt to poor forage conditions by increasing their grazing time and by dispersing more widely (Manteca and Smith, 1994). On good pastures, grazing times for domestic ruminants usually range between 4 and 9 h per day (Houpt, 2018), whereas grazing times of up to 14 h have been recorded on poor forage conditions (Arnold and Dudzinski, 1978). Ruminants have a limited time budget for grazing, mainly because they have to devote a significant amount of time to ruminate. Under very adverse conditions, fatigue affects an animal before its nutritional requirements have been met (Birrell, 1991). The effects of food shortage may be aggravated by high stocking rates and environmental factors such as water scarcity and high ambient temperatures.

Stocking density is one of the most important factors affecting forage availability and quality (Edwards, 1980; Allison, 1985; De Villiers et al., 1994). In many extensive systems stocking density is often thought to be low, but changes can arise suddenly, sometimes as a result of policy. For example, in the main Spanish Dehesa area, some farmers have increased stocking density to maximize EU subsidies (Prieto and Martín, 1994; Escribano et al., 2002; Gaspar et al., 2009). Although increasing stocking density is often linked with improvements in profitability (Escribano et al., 2006), as well as in herbage production and utilization (Macdonald et al., 2008; McCarthy et al., 2012a), this is frequently achieved at the expense of the individual animal performance and welfare (Stakelum and Dillon, 2007; Macdonald et al., 2008; McCarthy et al., 2012b). For example, high stocking densities have been associated with reduced body weight (Sharrow et al., 1981) and fertility (McGowan, 1981).

Herbivores select plant and plant parts depending on stocking densities (Provenza and Villalba, 2006) and high animal densities can increase competition for food resources and reduce selectivity (Bailey and Brown, 2011). Furthermore, the prevalence of non-preferred plants species under high densities can increase the risk of consumption of poisonous plants (Pfister et al., 2002) (see below). As well, high animal densities may increase social stress leading to disturbed grazing patterns (Blanc and Theriez, 1998). Still, the link between stocking density and livestock welfare in extensive systems is not straightforward. In a recent study, Müller et al. (2014) did not report a significant effect of the intensity of grazing on the live weight gain of individual sheep grazing on a semi-arid grassland steppe in Inner Mongolia. On a different study with sheep in the same area, the live weight gain per sheep was much lower at high than at low grazing intensity (Schönbach et al., 2012). Different systems of grazing management cause animals to forage in different ways (Provenza et al., 2003) and continuous grazing at low stock densities encourages selectivity and reduces diet and habitat breadth, whereas short- duration grazing at high stock densities increases diet and habitat breadth.

Under heat stress conditions, ruminants tend to avoid grazing during the hottest part of the day and thus reduce daily grazing time (Arnold, 1985). The extent of this reduction varies greatly between breeds. For example, European breeds of cattle reduce their grazing time during hot and humid days much more than zebu cattle. The main factor accounting for these differences in behavior is that the sweat glands of *Bos indicus* are larger, more numerous and more active than those of most breeds of *Bos taurus* (Macfarlane, 1964). Walking long distance between watering points and grazing grounds may take a considerable amount of time and reduce time available for grazing. Continuous irritation by flies may also reduce grazing time (Lefcourt and Schmidtmann, 1989). For example, in bad seasons, sheep may lose a great deal of grazing time due to irritation by *Oestrus ovis* flies (Blood et al., 1983).

Ruminants that graze in extensive systems are generalist herbivores, meaning that they evolved consuming diverse diets as opposed to monotonous pastures. A decrease in the diversity of foods and/or habitats may compromise animal welfare (Manteca et al., 2008; Villalba et al., 2011; Catanese et al., 2013). On the one hand, the inability to satisfy requirements for energy, protein, and minerals can lead to nutritionally unbalanced intake, health problems, and stress. On the other hand, the animal may continue foraging in order to satisfy the requirements for nutrients in lower concentrations, inevitably leading to overconsumption of the nutrient in highest concentration (Raubenheimer, 1992). Furthermore, diverse diets increase the likelihood of ingesting beneficial chemicals that enhance the health and welfare of animals (Villalba et al., 2010a). Thereafter, excess of some nutrients, homogenous food environments and the inability to express diet preferences can induce aversive behavior (Provenza, 1996), frustration (Rutter, 2010) or negative post-ingestive feedback (Forbes, 2007; Villalba et al., 2010b).

Animals vary in their acceptance of particular plants and herbivores develop food preference because of the dynamic interplay between flavor and post-ingestive feedback, which is determined by an animal's physiological condition and a plant's chemical characteristics (Provenza, 1996; Provenza and Villalba, 2006). Neural communication between what a ruminant tastes and smells and the subsequent reactions in the viscera enable ruminants to sense the consequences of food ingestion (Provenza, 1995). Animals learn to recognize specific plants and discriminate food through taste, visual, and olfactory signals. Bitter taste, for example, has been studied for its role in plant selection (Glendenning, 1994).

Individuals of the same species may also differ in their acceptance of particular plants. This variability may be partially explained by early grazing experiences (Arnold and Maller, 1977). Early experiences in utero and shortly after birth influence gene expression and have long term effects on grazing behavior (Provenza et al., 2003; Kappeler and Meaney, 2010).

As opposed to traditional rotational grazing at low stock densities, managing stocking density in a flexible and dynamic way can enhance plant production and diversity (Provenza et al., 2003; Campbell et al., 2006) and should be encouraged. Such highly qualified management of stocking density can greatly benefit animal welfare and improve vegetation abundance and plant diversity (Grissom and Steffens, 2013; Villalba et al., 2016). Further research is needed on the relationship between stocking rate and livestock behavior and welfare under different environments and grazing regimes.

When offered a diversity of feeds, individuals may be better able to select nutrients according to their specific needs and consequently achieve an adequate state of nutrition and well-being (Manteca et al., 2008). Management strategies that allow animals to express their feeding preferences create opportunities to reduce costs and enhance performance of grazing livestock.

Providing food and mineral supplementation can improve forage digestibility and feed intake and prevent many welfare problems related to nutrition. However, supplementing animals may not be feasible in very extensive systems. An additional problem is that some animals may be reluctant to eat supplements if they are not accustomed to them. When providing supplementary food, it is important to distribute it as widely as possible to avoid competition between animals.

Mixed-livestock stocking, defined as the simultaneous stocking and management of two or more animal species, has the potential to grow worldwide providing both economic viability and animal welfare benefits (Anderson et al., 2012). Using data envelopment analysis models on a sample of extensive farms from the Spanish Dehesa, Gaspar et al. (2009) reported that mixed-livestock farming (beef cattle, sheep, and Iberian pig) is a way to increase efficiency, reduce dependence on subsidies, and prevent adverse directional shifts toward unpalatable plant species. A major advantage of mixed-livestock is the better overall utilization of forage. Each animal species prefers different plant species and may use different parts of the landscape preferentially. Certain plant species that are toxic to one animal species may actually serve as forage for another species (Krueger and Sharp, 1978; Popay and Field, 1996). Food availability to the animals will vary depending of the species. For example, goats use resources that are not available as food to other species. Goats use the bipedal stance when feeding and may even climb trees, therefore reaching food unavailable to other ruminants. Goats also have a much higher rejection threshold for bitter tasting substances than sheep or cattle. This allows them to feed on shrubs rich in tannins (Bell, 1959). Mixed-species livestock is not a new livestock management concept and the ecological advantages of using such management systems have been extensively reviewed by Walker (1994). Nowadays, this type of production system may raise increasing interest both from being sustainable and profitable. Research on the impact of mixed-species systems on animal behavior, physiology and health is necessary to increase the implementation of such systems.

Early life experiences cause neurological, morphological, and physiological changes that shape the behavior of the animal in adulthood (McCormick et al., 2000; Dufty et al., 2002). From a management perspective, exposing animals early in their life to a diversity of foods and habitats can reduce the fear response to novelty and help the animals to adapt more easily to a diverse and variable environment. Numerous studies have shown that experience early in life can cause epigenetic changes that influence foraging behavior, habitat selection, and animal health (Provenza, 2008). Epigenetic effects suggest that future generations of livestock could be better adapted to the environment than their parents and should be given further importance in extensive livestock research as it can provide long-term benefits. Exposing pregnant mothers (Nolte and Provenza, 1992) or individuals early in life (Distel et al., 1994) are ways to improve intake of novel foods and decrease fearfulness. When sheep are placed in a new environment likely to elicit a stress response, they show a greater reluctance to eat novel foods compared with the same animals offered new food in a familiar environment (Burritt and Provenza, 1997). This may be particularly relevant when animals are moved from one area to another having a different plant community.

Precision livestock farming (PLF) technologies that can monitor foraging behavior could help to identify or even predict when and where forage is likely to be limited. As proposed by Rutter (2014) the integration of virtual fence technology with other sensors, both on and off the animal, along with external data such as weather forecasts, should allow smart systems to be developed that dynamically monitor and control grazing in a way similar to traditional, human-based shepherding. Such a system could act as a "virtual shepherd" (Campbell et al., 2020). However, it is important to bear in mind that, although PLF technologies have a great potential to support farmers, they are not a substitute for farmers' skills and experienced shepherds with a direct knowledge of animals' needs and behavior can accomplish many things technology cannot (Meuret and Provenza, 2015). Further barriers and limitations for PLF are discussed later on in this review.

Chronic Thirst

Water is often one the most limited resource under extensive conditions. Depending on ambient temperature and feed intake, water intake can vary drastically. Under thermoneutral conditions, water requirements range from about 4–8 L per kg of DM intake for cattle and about 2–4 L per kg of DM intake for sheep and goats. Under heat stress conditions, water requirements can easily double. Forage type and conditions affect water intake. Thirst increases when the water content of the forage is low. Likewise, forages with high concentrations of salt increase water requirements. Therefore, livestock need to drink more water under heat stress and when forage conditions are poor.

Two main factors can impair the consumption of water: water availability and water quality. Water is not always available near a good pasture. Livestock may then face a dilemma having to choose between forage and water. When watering points are widely spaced, the area available for grazing is reduced and resources far away from water may not be used at all. Some animals can cope with infrequent water access (once every 2–3 days for tolerant cattle and a bit longer for sheep and goats (Gregory, 2007). However, water shortage and intermittent water intake can cause detrimental physiological effects. In arid areas, animals can die from thirst in only a few days if they cannot find water.

Besides water availability, the quality of water has a direct impact on the welfare of animals. Access to water of poor quality can drastically alter the health of the animals. Drinking water may be contaminated by minerals, manure, microorganisms, and algae. These contaminants can impact the appearance, odor, and taste of drinking water as well as its physical and chemical properties. Some contaminants may directly impact animal health by causing disease and infection; others have a more indirect effect and may cause livestock to decrease their overall water intake. When water intake is suppressed, feed intake will also decrease, and, as a result, animals will gain less weight.

Contamination with manure can be a frequent problem when animals drink from ponds, as they may defecate into the water or carry manure on their hooves. In a Canadian study done over a 2-months period, yearling cattle gained 23% more weight and spent more time grazing when drinking clean water than when drinking directly from a pond (Willms et al., 2002). The authors argued that cattle have an aversion to drinking water contaminated with feces and suggested that dugouts contaminated with fecal material would reduce water palatability and intake. Lardner et al. (2005) reported an improvement of 9–10% in weight gain by cattle consuming treated water. Water that is contaminated with manure can become a hotspot for bacteria and algae growth, which in turn can cause diseases such as mastitis, urinary tract infections, and diarrhea (Galey et al., 1987; Metz et al., 1997; Chorus and Bartram, 1999; Brew et al., 2009).

Water quality is also affected by total dissolved salts or TDS. Based on field experience, Beede (2006) reported that an increase in TDS in drinking water can negatively affect the productivity and health of lactating dairy cows both within the environmental thermoneutral zone and during heat stress. High salt content water negatively affected sheep performance (Barrio et al., 1991) and the lactation performance of dairy cows (Solomon et al., 1995). High salt content water can also produce acute effects such as excessive salivation and diarrhea and may be especially difficult to monitor and control under extensive systems.

Water quality should be checked regularly. Small changes in water management can enhance health and performance (Brew et al., 2009). Reducing the concentration of TDS, blue-green algae and other microorganisms, preventing fecal contamination, providing fresh rather than pond water and cleaning watering devices regularly can all result in measurable improvements in livestock welfare and performance (Brew et al., 2009). It may be useful to test the quality of the water on each property. Despite a lack of solid research information to set validated and practical guidelines for ruminants, many different water quality guidelines for farm livestock are suggested in the literature and can be useful (e.g., Beede, 2012).

Toxic Plants

In extensive grazing systems, animals encounter a diversity of plants that contain plant secondary compounds (PSC). As reviewed by Pfister et al. (2016) and Provenza et al. (2003), PSC are highly diverse chemical structures with a wide variety of actions on animal health and behavior (Durmic and Blache, 2012). Interestingly, a specific PSC can have both detrimental and/or beneficial effects on animal welfare depending on the form and the dose ingested, the duration of ingestion, and the species exposed (Greathead, 2003). Among negative impacts, PSC can alter nutrient utilization, digestive function, respiratory and cardiovascular function, immune function, as well as deterioring the nervous system and reproductive capacity (Vercoe et al., 2009; Villalba et al., 2016). Herbivores have acquired behavioral and metabolic adaptations that allow them to cope with PSC. The main behavioral adaptation is the capacity of herbivores to develop food aversions when ingesting PSC, because some of these compounds induce nausea (Provenza, 1996). However, not all PSC cause food aversions (Pfister et al., 2010) and delayed toxic effects can limit the ability of herbivores to form food aversions (Villalba et al., 2016). The ingestion of toxic plants by extensively kept animals can thereafter be a source of pain and suffering (Roger, 2008; Pfister et al., 2016). Raising cattle breeds which are not adapted to tropical environments with subsequent exposure to unfamiliar plants can compromise their welfare and production (Eisler et al., 2014). Furthermore, if food is scarce, animals may eat less palatable plants, some of which can contain toxins. Animals may die because of toxic plants that they would avoid eating under normal circumstances (Krueger and Sharp, 1978; Provenza and Balph, 1990; Provenza et al., 1992).

Conversely, as reviewed by Villalba et al. (2016), plant secondary compounds can also have a beneficial effect on health when they are ingested in the right quantity, for the right amount of time, or in the right combination. For example, PSC have recognized actions on the control of gut pathogen load through different mechanisms (e.g., Athanasiadou et al., 2001; Martínez-Ortiz-de-Montellano et al., 2010). Recent results suggest that parasitized sheep and goats increase preferences for antiparasitic PSC when experiencing parasitic burdens relative to non-parasitized animals (Osoro et al., 2007; Martínez-Ortiz-de-Montellano et al., 2010; Villalba et al., 2010b; Juhnke et al., 2012). Other studies suggest livestock self-medicate by grazing specific medicinal plants when ill (Grad et al., 2009). Thereafter herbivores may learn about the benefits of specific PSC for mitigating discomfort and pain associated with certain health pathologies.

The medicinal effects of PSC have a great potential to improve both the health and welfare of ruminants kept in extensive systems. As commented by Villalba et al. (2016) the biochemical diversity of plants offers animals the opportunity to enhance their health and well-being. Eating diverse diets thus provides herbivores all the advantages of bioactive compounds such as anti-parasitic agents and immunomodulators daily with health maintenance effects. Herbivores exposed to varied diets may also learn about the benefits of specific plant secondary compounds as natural analgesics. Management practices that promote plant diversity and enhance animals' diet selection offer ways to reduce the impact of some health pathologies.

ENVIRONMENT STRESSORS

Thermal Stress

Depending on its intensity and duration, heat stress may negatively affect livestock health by causing metabolic alterations, oxidative stress, immune suppression, and death (reviewed by Lacetera, 2019). The effects of heat stress on animals are expected to be similar independently of the production system. However, extensive environment are highly variable and heterogeneous in terms of climate, pasture quality, and topography. Climate is changing toward warmer and drier conditions accompanied with poorer vegetation growth in pastures and higher ambient temperatures and solar radiation (Silanikove and Koluman, 2015). Extensive livestock production systems will come under increased pressure with predicted climate change scenarios (Rust, 2019).

Heat stress is one of the greatest challenges faced by producers and their livestock in many regions of the world. Heat stress reduces feed intake by 15–40% and increases maintenance requirements by 30% (NRC., 2007; Hooda and Singh, 2010; Hamzaoui et al., 2013; Rhoads et al., 2013). The decrease in milk production under heat-stress situations is directly linked to reduced feed intake, while the energy needs of the animal increase. In addition, heat stress reduces protein and fat contents in the milk, inhibits rumination, and causes immunosuppression, thereby increasing the incidence of some diseases. Heat stress drastically reduces reproductive performances by reducing the synthesis and release of LH and GnRH, which are essential hormones for ovulation and expression of oestrus behavior. Under heat stress conditions, cattle increase the time they stand still, decrease the time they spend resting, and moving around (Cook et al., 2007; Allen et al., 2015). This allows cattle to maximize body surface area in contact with air but increases the risk of lameness. Thermal stress increases thirst. Hyperthermia and dehydration have been associated with an increase in neuromuscular fatigue and incoordination of movement in animals. This means that in hot climates the risk of injury can increase.

The feeling of warmth depends not only on the ambient temperature, but on the effective temperature which results from several factors, including ambient temperature, relative humidity, wind, and solar radiation. The temperature and humidity index (THI) is often used to estimate the effective temperature based, as the name suggests, on ambient temperature, and relative humidity. An adjusted THI for solar radiation and wind speed has been proposed by Mader et al. (2006).

Tolerance to thermal stress varies strongly depending on the species and breed. Dromedary camels are known for their high heat tolerance. Besides their high capacity for sweating, camels are also able to dissipate a significant amount of heat by convection, as the vasodilation of peripheral vessels leads to an increase in cutaneous blood flow and heat dissipation (Abdoun et al., 2012). Breeds of cattle differ in their capacity to thermoregulate and adapt to hot environment. For example, Nellore cattle are more tolerant of tropical heat conditions than Holstein breed (McManus et al., 2009). Moreover, factors such as milk production levels, the quantity and quality of food, health status and hydration levels of the animals can exacerbate the effects of high temperatures (Silanikove, 2000). Under extensive management systems, poor forage quality during summer and reduced water availability can increase the negative impact of heat stress. For example, in cattle in the Southern US, fertility is reduced from around 50% in winter to less than 15% in the summer (Thatcher and Collier, 1986). Most of the published data available on the impact of heat stress have been obtained under experimental conditions and few studies on the impact of heat stress on extensive livestock in field conditions are available.

Cold can also be a welfare problem for extensive livestock. Energy requirements for maintenance are 20% greater in cold winters, and if animals are wet and not protected from the wind, these requirements can double (NRC., 2007). If forage is available and highly digestible, animals can increase energy intake and cope with cold stress. However, when ambient temperature is near freezing both forage availability and digestibility decrease (Adams, 1987). During long and cold winters, ewes with very low body conditions can die from exhaustion. A fleece that is soaked by rain and mud provides little protection against cold. Hypothermia of the newborn due to cold stress is a main cause of neonatal mortality (Dwyer, 2008). Newborn lambs, once dry, are much more sensitive to cold than their mothers. For an adult ewe with full fleece, the approximate lower critical temperature is −20°C whereas dry lambs can suffer cold stress under 15°C (McCutcheon et al., 1983). It is therefore essential to provide areas protected from wind and rain, especially during the birth period.

Keeping appropriate species and breeds, especially those adapted to local areas climate conditions is fundamental for sustainability of the production system. Physiological characteristics of goats provide them an advantage over other ruminant species in harsh environmental conditions and dwarf goats are particularly resistant in arid regions. A long-term strategy aims to select for heat- and cold-tolerant breeds. Marker-assisted selection will become more relevant for the genetic improvement of extensive production animals.

Shade structures can reduce total heat load by 30–70% (Blackshaw and Blackshaw, 1994; Muller et al., 1994a; West et al., 2003). Shade shelters can have a beneficial effect on productivity and reproductive performance (Gaughan et al., 2010). During hot weather, dairy cows have a strong motivation to seek shade to avoid heat and sunlight (Schütz et al., 2008, 2009). Shaded cows under South African Mediterranean summer conditions had higher milk production, lower plasma cortisol concentration, lower rectal temperatures and respiration rates that non-shaded cows (Muller et al., 1994b). Cows with access to shade spent more time feeding during the day and less time standing (Muller et al., 1994c). Under summer Mediterranean conditions, the respiration rate of shade sheep (80 breaths per min) was 56% lower than in non-shade sheep (125 breaths per min) (Silanikove, 1987). In semi-arid and arid environments provision of shade structures is a good investment. Access to woodlands and provision of trees and shrubs also can be important sources of shade.

Feed supplements can help livestock cope with thermal stress, as they allow the animal to maintain water balance and nutrient intake and provide for specific nutritional needs during heat stress (Renaudeau et al., 2012; Salama et al., 2016). As mentioned earlier, optimization of water intake by providing easy access to good quality water is especially relevant under heat stress conditions.

Despite strong practical barriers, extensive systems can also benefit from engineering solutions to mitigate the impact of heat stress. For example, providing even very brief access to shade and sprinklers can result in lower body temperatures for up to 4 h (Kendall et al., 2007). The risk of hypothermia in newborn animals such as lambs can be reduced using wind breaks. Additionally, as low body weight at birth increases the risk of hypothermia, ensuring adequate feed intake during pregnancy is important (see above).

Predation

Predation accounts for a small percentage of total losses in livestock raised in extensive management systems and may range between 0.2–0.8% for cattle and 4–6% for sheep in the US (summarized in Laundré, 2016). These figures include not only losses caused by wild predators but also by domestic dogs, which in many parts of the world are the main predators of livestock. Similarly, wolf depredation affected annually 0.69 ± 0.14% of free-ranging livestock in the region of Asturias, NW Spain (Fernández-Gil et al., 2016). From a global perspective, livestock losses due to predators are relatively low and non-predator losses such as mortality due to diseases or malnutrition are much higher. However, predation losses are not evenly distributed and some farmers experience much higher losses than others (Nowak et al., 2005; Gazzola et al., 2008). Furthermore, in some regions conflicts between farmers and predators have recently increased, leading to a reduced acceptance of wild carnivores (Lescureux et al., 2018). For example, the number of dead livestock caused by predation has steadily increased in France over the last 12 years, with 1,000 more animals killed each year, despite the implementation of protection measures against predators (Meuret et al., 2017). Predators may therefore represent a threat to pastoral farming systems in areas where wild carnivores are abundant.

The indirect effects of repeated predator intrusions on the welfare of livestock animals are often unrecognized as the cause-effect relationship is often difficult to establish (van Bommel and Johnson, 2017). Nevertheless, some studies suggest significant indirect effects. For example, Steele et al. (2013) reported significant effects of the presence of wolves on weaning weights and conception rates of cattle in Wyoming. Similarly, Ramler et al. (2014) found that calves in herds that have suffered wolf attacks have lower average body weights. Some evidence suggests that cattle exposed to predators forage less efficiently and thus experience lower average daily weight gain (Ashcroft et al., 2010). Cattle herds exposed to predators can also have lower conception rates, either due to stress (Howery and Deliberto, 2004) or because cattle used as replacements do not breed as efficiently as those lost to predators (Ashcroft et al., 2010). Laporte et al. (2010) reported that cattle moved closer to other cattle and increased path sinuosity in the presence of wolves in Southwest Alberta, Canada. Also cows with calves increased their vigilance levels when predation risk was higher (Kluever et al., 2008, 2009). As documented in wild species, behavioral changes such as increased vigilance and grouping appear to be common response to predator presence in livestock. Predators may therefore have an impact on their prey, not only by killing but also by scaring them. According to several studies, livestock escape predator intrusions as often as 80% of the time (Mech et al., 2001). This means that "survivors" may have experienced fear. Fear is an adaptive response, essential to the survival of predated species, that normally gives rise to defensive behavior or escape. However, the exposure to repeated fearful situations can lead to negative emotional states such as anxiety (Boissy, 1995). Repeated exposure to acute stress can lead to chronic stress with long-lasting consequences such as reduced immune function, suppress reproduction, and reduced production (Dwyer and Bornett, 2004).

Farmers report a long-lasting reluctance from their herd in using certain places where a wolf attack occurred (Meuret and Provenza, 2015; Garde and Meuret, 2017). Such practical local knowledge should be given a greater value. A complex welfare issue such as predation would greatly benefit from bottom-up approaches and joint learning amongst scientists and the farming community.

Predators can have a long-term effect on the use of space by livestock and this in turn could negatively affect their welfare and performance (Meuret et al., 2017). This effect is often referred to as "the landscape of fear" and is based on the assumption that under predator pressure, animals change their use of the landscape to seek safer pastures (Hernández and Laundré, 2005; Laundré et al., 2010; Sheriff et al., 2010), which can be overgrazed and thus lead to lower foraging efficiency (Christianson and Creel, 2010). Most studies on the "landscape of fear" have been done in wild animals and an increasing number of authors are questioning the existence of the landscapes of fear in wild herbivores. In particular, the extent to which prey movement patterns actively minimize predation risk across space and time is still controversial (Creel et al., 2008). Indeed, there is a debate regarding the relative importance of proactive vs. reactive spatiotemporal responses by prey to predators and the risk of predation (Creel, 2018). In the recent years, advances in tracking technology can provide a huge amount of information to better understand behavioral patterns of prey and predators. In a recent study, Cusack et al. (2020) assessed the spatiotemporal response of GPS-collared female elk to the risk of predation by wolves during winter in northern Yellowstone. The study highlights a notable absence of spatiotemporal response by adult female elk to the risk of predation posed by wolves. Further, there was no evidence of any reactive responses of individual elk to the presence of wolves in proximity. These results suggest that predator-prey interactions may not always result in strong spatiotemporal patterns of avoidance.

Wherever possible, strategies that allow the coexistence of extensive livestock with predators should be encouraged and include using electric fences, night confinement, close supervision of livestock during high risk periods such as lambing, removing dead animals to avoid attracting predators and supervision of weak, sick, and young animals. Depending on the context of a given local area and herd management, some of these measures are difficult to implement in a feasible way without affecting negatively the welfare of the farmers and their livestock (Meuret et al., 2017). The huge capacity of adaptation of wild carnivores such as the wolf to human practices is an additional constraint to the efficiency of such measures. Overall, however, livestock guarding dogs (LGDs) remain the most effective non-lethal method to reduce losses to predators. The ability of LGDs to protect livestock from predators has been documented in a range of contexts (reviewed in Rigg, 2001; Gehring et al., 2010; Yilmaz et al., 2015). A recent LGD program implemented in Portugal showed that the majority of farmers considered that the advantages of having LGDs outweighed the costs and they were interested in maintaining them in their flocks (Ribeiro et al., 2017a). The lack of traditional knowledge in regions where LGDs have never been used or where their use was discontinued following the eradication of large carnivores can be an obstacle to their implementation. However, LGDs have been successfully introduced where there was no previous tradition of using them, such as in Australia, Namibia, the US and more recently in the Nordic countries and Germany (e.g., Coppinger et al., 1983; Hansen, 2005; Levin, 2005; Marker et al., 2005; Otstavel et al., 2009; Reinhardt et al., 2012; van Bommel and Johnson, 2012). A survey by van Bommel and Johnson (2012) in Australia reports that 95% of participants thought their dogs were a cost-effective way of protecting livestock. Besides the direct impact in reducing damages from predation, producers also report that their livestock become calmer, and are therefore easier to handle and more productive, in the presence of LGDs. The main factor influencing how well LGDs work in Australia was the number of livestock they are required to protect. It is important to remember that dogs work in a group, and thus it is important to have a well-balanced working group of dogs (e.g., Iliopoulos et al., 2009).

However, despite the efficacy and widespread use of LGDs, many producers still struggle to raise these dogs in an effective manner. A mismatch is often found between traditional literature and current problems and expectations (Liebenberg, 2017) and there is a lack of knowledge on how to breed and train LGD effectively (Liebenberg, 2017). In particular, socialization of LGDs is becoming increasingly important to prevent aggressions toward people and should be balanced with the need for dogs to bond with livestock. A LGD can fulfill the role of protector while being sociable to persons. Lack of selection for working dogs, inappropriate cross breeding and poor training techniques are additional bottlenecks for the successful use of LGDs. Finally, the general public often does not know how to behave in the presence of LGD, which may cause conflicts in touristic areas. Promoting networking and knowledge-exchange between farmers, as well as providing them with proper technical support on raising and training LGDs to avoid undesirable behavior may help to solve or prevent conflicts (Ribeiro et al., 2017b).

Livestock Handling

Animals are usually handled less often in extensive systems compared with intensive ones, thus welfare problems related to human-animal relationship may ensue. Farm animals may associate humans with rewarding and punishing events that occur at the time of their interactions and may thus develop conditioned fear responses to humans (Hemsworth and Colleman, 2011). In extensive management systems, human-animal interactions are mostly sporadic and seasonal. Additionally, handlings of extensively managed livestock is usually aversive as it includes procedures such as vaccination, restraint, and shearing. For example, most beef cattle in northern Australia are handled, at most, twice annually when they are herded for weaning (Bortolussi et al., 2005). The first close encounter between calves and stockpersons is at the time of weaning when calves undergo numerous aversive procedures (Petherick, 2005). Calves associate humans to aversive situations and show fearful reaction in future handlings. When herding livestock, the use of fast, sudden, unexpected movements, and yelling provokes fear. Cattle are sensitive to auditory interactions with humans showing a similar aversion to hitting as to shouting by humans (Pajor et al., 2000). Extensively managed animals are therefore more likely to associate humans with negative experiences rather than rewarding ones such as routine food deliveries. The lack of regular human contact in extensive systems can contribute to livestock suffering fear and distress during herding and handling. Fearful animals are difficult to handle and may react excessively and injure stockpeople and themselves (Petherick, 2005).

As in other production systems, good stockmanship is the key to minimizing animal welfare problems in extensive livestock (e.g., cattle, Petherick, 2005). There are strategies to improve human-animal relationships in extensively managed systems and reduce fear reaction from the animals. Some animals with calm temperament seem to find management procedures less stressful (Curley et al., 2006; Petherick et al., 2009; Cooke et al., 2012). Low-stress stockmanship techniques are an effective tool to reduce livestock stress during herding and handling (https://stockmanship.com/; Hibbard and Barnes, 2016). Those techniques aim to drive animals properly minimizing the use of negative interactions such as unnecessary force or noise and preventing fear reaction. Training programs for stockpeople can offer good opportunities to improve human–animal interactions. In many areas, livestock are gathered on horseback or using motorcycles, and cattle can be trained from an early age to move calmly and follow a person on horseback or motorcycle (Fordyce, 1987; Petherick, 2005). *Bos indicus* breeds and crossbreeds tend to be "followers" and this behavior can help for moving them quietly (Grandin, 1998). Rewarding experiences, such as provision of a preferred feed or positive handling, around the time of the procedure may reduce the aversiveness of the procedure and the chances that animals associate the negative component of the procedure with humans (Hemsworth, 2007). For example, rewarding sheep with food improves subsequent handling (Hutson, 1985; Grandin, 1998). Finally, well-designed handling facilities can greatly improve animal welfare by reducing fear and injuries [e.g., Grandin (1993, 1997)].

PAIN, DISEASES, AND OTHER HEALTH RELATED PROBLEMS

Pain

Pain is a major welfare problem and the main causes in farm animals (both in extensive and in intensive systems) are diseases and injuries (including health problems caused by toxic plants and injuries caused by predators) as well as some husbandry practices. In addition, neonatal mortality is a health-related issue that can cause substantial suffering in animals (see below).

A thorough discussion of pain physiology and assessment is beyond the scope of this paper. However, it is worth emphasizing that newborn ruminants and pigs experience pain. Moreover, some evidence suggests that pain shortly after birth can increase pain sensitivity and this effect is likely to persist for months or years. Animals do not habituate to chronic pain, instead they become more sensitive so that pain increases with time. Ideally, regular observation of the animals' behavior to identify signs of pain as early as possible is of paramount importance to ensure their survival and the sustainability of the production system. However, the detection of behavioral expression of pain may be more difficult in animals under extensive conditions. Species that are traditionally managed extensively such as ruminants show subtle signs of pain as they have evolved as prey species (Romeyer and Bouissou, 1992; Dwyer, 2004). For example, pain management in sheep is often inadequate and one of the reasons given by veterinarians for not administering analgesics to sheep in pain is the alleged difficulty to identify and assess pain in this species. Main signs of pain include reduced feed intake and rumination; licking, rubbing, or scratching painful areas; reluctance to move; teeth grinding and lip curling; altered social interactions; changes in posture to avoid moving or causing contact to a painful body area. More recently, a Sheep Pain Facial Expression Scale (SPFES) has been developed to identify sheep suffering pain caused by mastitis or footrot (McLennan et al., 2016).

The difficulty in pain identification can be compounded in many extensive systems where animals have little contact with humans, with infrequent handling. Gathering livestock to identify and treat sick animals may be difficult, and prevention of disease is of paramount importance. For example, foot bathing should be done to prevent footrot in sheep when environmental conditions are getting warm and moist. Rapid diagnostic of diseases represents a huge challenge in extensive systems.

Painful Husbandry Practices

Independently of the production systems, management practices such as castration, tail-docking, dehorning, disbudding, branding, nose ringing, and mulesing (i.e., cutting wool-bearing and wrinkled skin from the perineal region and adjoining hindquarters of sheep) are stressful and painful procedures for animals. Several of these procedures induce acute pain that lasts several hours and is followed by chronic pain which can last more than 48 h (Stafford, 2017; Adcock and Tucker, 2018). As explained before, pain assessment relies mainly on general changes in behavior, as they are sensitive and non-invasive indicators of pain. For example, behavioral changes such as lip curling, trembling, vocalization, and abnormal postures have been described in lambs undergoing tail-docking or castration (Molony et al., 2002; Fitzpatrick et al., 2006). Guesgen et al. (2016) described changes in the ear posture of lambs associated with the negative experience of pain after tail docking using a rubber ring.

Besides being painful to the animals, such procedures are unpleasant to livestock producers. In some cases, evidence of benefits from a given practice is lacking and the practice should be abandoned. For example, tail docking of dairy cows is routinely done in some countries to reduce the risk of mastitis, but there is no evidence it has any effect. In other cases, less painful alternatives are available and should be adopted. For example, although both practices are painful, disbudding of young calves, or kids is far less painful than dehorning at a later age. When a procedure is clearly justified and no alternative is known, then pain mitigation methods should be used as much as possible using the least painful method plus administration of anesthesia and post-operative analgesia. However, lack of knowledge of pain-management practices has been identified as a primary barrier preventing the routine adoption of pain mitigation strategies (Nordquist et al., 2017).

Tail docking is frequently done in sheep kept in extensive conditions and will be discussed below to illustrate general principles applicable to other painful husbandry practices. It is thought that tail docking reduces the risk of fly strike in sheep by preventing build-up of fecal material (called "dags") on the tail, breech, and hindquarters. While some studies show that daggy sheep are more likely to be struck, the relationship between tail docking and dags is unclear. Indeed, conflicting results have been obtained when comparing the incidence of fly strike in docked and undocked sheep (Sutherland and Tucker, 2011). Overall, the justification for tail docking in sheep varies on a flock by flock basis depending on the geographical region, the breed of the animal and other management practices. Routine tail docking is unlikely to benefit sheep that do not have wool (hair breeds and some dairy sheep) or that are kept in regions with low incidence of blowfly strike. In some cases, tail docking is done because of tradition and this is not acceptable on animal welfare grounds.

The application of rubber rings within the 1st week of life seems to be the most frequently performed procedure. The rubber ring reduces blood flow to the distal portion of the tail, which eventually becomes necrotic and sloughs off. In some cases, a clamp is applied for 10 s next to the rubber ring as a method to crush and thereby destroy the underlying nerves. Lambs tail-docked with rubber rings show elevated cortisol levels and spend more time in abnormal postures and active behaviors associated with ischemic pain compared with control lambs (Kent et al., 1993). When the tail is docked, it is recommended to leave a minimum of three palpable coccygeal vertebrae in the tail stump (covering at least the anal region and vulva of the animals). Application of a clamp associated with ring tail docking reduces pain. Local anesthetics reduce acute pain. Following tail docking, lambs receiving nonsteroidal anti-inflammatory drug show less pain-related behavior compared with lambs receiving no pain relief, and the magnitude of the effect can be substantial (Small et al., 2014). Important considerations for the use of analgesic drugs in sheep include the ease of application and the duration of their effect. Age has very little effect (if any) on the pain caused by castration and tail docking.

Despite the proven efficacy of various nonsteroidal anti-inflammatory drugs (NSAID) and local anesthetic as discussed in the extensive reviews of Coetzee (2011) and Stafford et al. (2005, 2006), there is limited use of these products by farmers and practitioners during husbandry procedures. Local anesthetic injections are rarely used during routine husbandry procedures because of practical and economic constraints. Main practical limitations to the use of anesthetics arise from the delayed onset of action and the need for veterinary administration. The anesthetic effectiveness of lidocaine under experimental conditions has been reviewed (Rault and Lay, 2011) and found not to be immediate and of limited duration. In case of the use of intratesticular injection of lidocaine with adrenaline, it takes the lidocaine 3 min to reach the testicular cordons (Haga and Ranheim, 2005). This can require double handling of animals and a time delay between administration and procedure, both of which are huge barriers for its application on commercial conditions, especially in extensive production systems.

Genetic strategies such as breeding less wrinkled Merino sheep or polled animals which obviate the need to perform painful procedures such as mulesing or dehorning are important long-term welfare solutions. Intensive genetic research and breeding programs are underway, but this is a long-term objective (e.g., James, 2006; Scobie et al., 2007).

Ensuring that pain management becomes mainstream on-farm will be a critical challenge for all livestock industries, both intensive and extensive. However, as mentioned before, the use of anesthesia remains a big constraint. Recently, topical anesthesia has been reported to be effective in ameliorating wound pain and improving healing during mulesing, castration, and tail docking in sheep and castration in calves. Lomax et al. (2010) present evidence that alleviation of pain up to 4 h is achieved for lambs undergoing surgical castration plus surgical or hot iron tail docking using a spray-on topical anesthetic. Significant pain alleviation and improved recovery were also reported in lambs for up to 24 h after mulesing through the use of topical anesthesia (Lomax et al., 2013). Topical anesthesia reduced the pain up to 24 h in calves undergoing surgical castration (Lomax and Windsor, 2013). According to the authors, administering the product topically during and immediately postprocedure allows for rapid onset of anesthesia (within 1 min on the basis of sensory testing results). Long lasting pain should then be controlled through the use of long-action analgesia. Further field studies on the development of feasible and effective protocols to minimize acute as well as chronic pain associated with husbandry procedures should be undertaken in extensive managed livestock.

Immunocastration and leaving males intact are two alternatives to castration. Positive results have been experienced with regards to immunocastration (GnRH vaccine) in extensively managed *Bos indicus* in Brasil (Amatayakul-Chantler et al., 2013) and commercial Dohne Merino rams maintained extensively on kikuyu pasture in South Africa (Needham et al., 2016). To be effective the GnRH vaccine should be applied twice, strictly respecting the time between the two injections. Correct application of the vaccine is essential for its effectiveness.

Diseases and Injuries

Some diseases are more likely in extensive systems than in intensive ones. For example, internal parasites such as nematodes and external parasites such as mites and ticks are significant causes of diseases in extensive livestock. Importantly, some breeds such as *Bos indicus* genotypes are more resistant to parasites such as ticks and helminths (Frisch and Vercoe, 1984). Hoof injuries due to footrot are additional factors that contribute to poor health and pain of livestock (Raadsma and Egerton, 2013).

Several factors can represent a risk for disease under extensive management systems (Goddard, 2016). For example, herds with different sanitary states can share common grazing areas and water points which raises biosecurity issues. Disease control measures such as quarantine, vaccination and disinfection are more difficult to implement in extensive management systems. Cooperation between herders may be difficult as well, although it is essential to plan disease control measures. Treatment of sick animals can be considerably difficult since restraint facilities that allow close examination of the animal and treatment are rarely available in the extensive lands.

Livestock-wildlife transmissions of diseases can happen both in intensive and extensive systems. However, in extensive systems the main methods to control disease transmission may be difficult or impossible to apply. Some extensive production systems allow a greater interface between domestic and wild animals. With livestock and wildlife sharing the same ecosystems, several diseases can be transmitted among them. Those diseases can be caused by viruses, bacteria, and parasites. Pathogen transmission at the livestock–wildlife interface is frequently bi-directional (Bengis et al., 2002). For example, livestock have introduced several pathogens, such as bovine brucellosis and tuberculosis bacterium, to naïve wildlife populations in North America (Miller et al., 2013). In Africa, disease status associated to extensive livestock systems was reported as a threat to the existence of traditional pastoral society and wildlife resources (Kock et al., 2002). Health problems associated to contaminated water is an additional disease hazards as commented earlier.

In extensive systems, the difficulty to quickly recognize an injured or sick animal impairs efficient health care. Changes in animal behavior indicative of injury or disease, such as reduced locomotion and reduced feed intake could be automatically detected, and the farmer alerted so that rapid treatment could be provided (Rutter, 2016). PLF technologies could help farmers detect health issues. Although PLF systems were initially developed for use in more intensive systems (Berckmans, 2014), there is no reason why they should not be used in extensive systems. PLF technologies can provide continuous 24/7 monitoring of the animals and facilitate the detection of injured or sick animal. PLF can help farmers to make extensive systems more efficient without necessarily making them more intensive (Rutter, 2016).

Still, it is important to be aware of the risks and limitations of PLF technologies. First, PLF do not replace good stockmanship but should be only used as a tool to help farmers monitor livestock. Farmers cannot rely entirely on PLF technology and must be prepared to respond adequately when the system fails. Second, PLF data are sometimes difficult to interpret and the use of applications may need appropriate training (Rutter, 2016). Another potential barrier to the uptake of PLF technologies is the availability of reliable internet access, especially in the remote, rural location typical of many extensive farms. To access cloud services, farmers need reliable internet access, and more needs to be done to ensure rural communities can have the benefits of fast and reliable internet access. Finally, PLF represents a substancial financial cost. A survey of Scottish sheep farmers (Morgan-Davies and Lambe, 2015) found that the cost of the equipment was the main barrier to the adoption of Electronic Identification. Cost of PLF may represent a big impairment for its application in many extensive systems in the world.

Neonatal Mortality

Neonatal mortality is a concern in both intensive and extensive systems. Pre-weaning mortality rates of extensively kept livestock have been estimated (summarized in Dwyer and Baxter, 2016) to be around 9% in beef cattle, 15% in pigs, 15% in sheep, 20% in goats, and 30% in camels. Nearly 50% of pre-weaning mortality in cattle and sheep and 20% in pigs occurs within the first 3 days of life (Patterson et al., 1987; Nowak et al., 2000; Edwards and Baxter, 2015). Besides being a strong economical concern for the sustainability of extensive production systems, neonatal mortality raises animal welfare issues. A dying neonate can experience breathlessness, hypothermia, hunger, sickness, and pain (Mellor and Stafford, 2004). The mother may experience frustration, anxiety, inability to show maternal behavior and pain from a full udder (Dwyer and Baxter, 2016).

Causes of mortality of neonates born in extensive systems are diverse. Birth related injury plays an important role in the deaths of 80% of neonatal lambs (Haughey, 1993) and it is a major causal factor in beef calf mortality (Barrier et al., 2013). Nearly half of all calf mortality in first parity heifers and a quarter of all calf mortality in cows are associated with dystocia (Eriksson et al., 2004). The relative size of the neonate compared to the mother's size is a risk factor for injuries of the neonate during birth. Livestock born from dystocia are usually less vigorous and take longer to ingest the colostrum. Long and difficult parturitions are usually attended by people in intensive or semi-extensive systems. In extensive management systems, assistance during complicated parturitions may be delayed or impossible which increases the risk of death of the newborn. In extensive systems, neonates are vulnerable to thermal stress. Nearly half of all perinatal lamb losses are attributed to hypothermia under cold, wet, and windy weather conditions at lambing (Dwyer, 2008). Newborn kids and piglets are particularly susceptible to cold stress. In arid and semi-arid environments, high ambient temperatures and dehydration of the mother can impair milk ingestion and increase the risk of neonate mortality as well. In pigs kept in extensive systems with loose farrowing, crushing of the piglet by the mother is a major source of neonatal mortality (Edwards et al., 1994). Predation of newborn animals is another source of neonatal death, especially lambs, and kids.

Early suckling is essential for immunity transfer. In many domestic species, neonates do not acquire maternal immunity through the placenta. Instead, they depend entirely on passive immunity transfer through colostrum intake. Thus, neonates are born vulnerable to infectious diseases until colostrum intake and any delay in colostrum intake will increase the risk of disease in the neonates. Low birth weight and low vigorous newborn, combined with poor quality colostrum which can be attributed to poor maternal nutrition, impair immunity transfer and hence the health of the neonate. In camels, 50% of mortality occurs the first week of life. Inadequate passive immunity transfer via colostrum intake partly explains high neonatal mortality in camels (Kamber et al., 2001).

In extensive management systems the behavioral abilities of mother and young are especially relevant to reduce neonatal mortality. Appropriate maternal behavior and the newborn behavioral response are key features for the newborn survival (Dwyer and Baxter, 2016). Given that human intervention during parturition is difficult or sometimes impossible in extensive management systems, the provision of an appropriate shelter is expected to enhance neonatal survival.

CONCLUSIONS

This article has highlighted the animal welfare challenges most likely to be found in extensive systems. Unlike intensive systems, which tend to be rather homogeneous across countries, the conditions encountered by animals in extensive systems are variable depending on climatic conditions, topography and pasture quality, among other factors. Therefore, some welfare problems of extensive systems may be a major concern in some parts of the world but not in others.

Nevertheless, extensive systems are by no means free of welfare problems, although these are likely to be (at least to some extent) different in nature from welfare problems found in intensive systems. Animal welfare is complex, multidimensional concept that includes the biological functioning of the animals (i.e., their health and nutrition), their affective state and whether they are able to display their natural behavior. We suggest that the widely held assumption that extensive systems are better than intensive ones from an animal welfare standpoint partly results from the fact that the general public may prioritize "naturalness" as the most important aspect of welfare. Although natural behavior is indeed an important aspect of animal welfare, it is widely accepted that a proper assessment of animal welfare requires that the other two aspects are also considered.

Welfare challenges in extensive systems can be addressed using a variety of strategies. Selection of animals well-suited to the climatic and nutritional environment appears to be of paramount importance. This selection means not only that locally adapted breeds should be used whenever possible, but also that selection of genetic lines or varieties that offer advantages in terms of reduced neonatal mortality or resistance to specific diseases, among others, must be implemented.

Other improvement strategies are related to management and husbandry, and close supervision of animals is very important. Admittedly, such a close supervision may be very difficult in very extensive production systems, but both changes in husbandry practices and / or using technological developments that allow remote supervision of the animals or pasture conditions are a priority area.

Some welfare problems of extensive systems require very specific management practices. One example is the presence of livestock guarding dogs (LGD) as a non-lethal method of predator control. Studies in many countries have shown that LGD are useful—particularly when used together with other measures, such as close supervision of animals and night fencing—to reduce losses to predators. In those areas of the world when predation is now a problem but the use of LGD was discontinued many years ago, it is important to implement programs of knowledge-exchange among producers.

Finally, welfare assessment tools are needed to identify problem areas and monitor improvement strategies. One major difficulty here is that, to a large extent, welfare assessment protocols have been designed mainly for intensive systems. Although some of them can be partly adapted to extensive systems, adjustments are needed. Hence, welfare assessment protocols for extensive systems of livestock production are urgently needed.

Extensive systems of livestock production play a key role in the livelihoods of many people around the world and in many areas are the only way to produce food for humans. Moreover, such systems are important as they contribute to the conservation of genetic diversity of livestock species, rural development and, very often, biodiversity conservation. However, in order to guarantee their long-term social and economic sustainability, an effort must be made to realize that even though they offer clear advantages over intensive systems in some areas of welfare, they are not free of challenges. Furthermore, research aimed at developing welfare assessment tools which can be used in extensive systems is needed.

Many animal welfare issues in extensively kept animals are complex and face multifactorial challenges that may be better addressed by alternative approaches to the traditional top-down dissemination of knowledge from science to practice. There is growing policy interest in more "bottom-up," practice-led, collaborative approaches to innovation which involve livestock producers (Brunori et al., 2013). These practice-led approaches respond to the demand for innovation to solve local problems using practical knowledge and creativity at the farm level (Vogl et al., 2016; Molnár et al., 2020). A greater value should be given to participatory approaches to practice-led innovation in addressing complex, multi-factorial issues (van Dijk et al., 2019). More opportunities are needed to enhance the integration of such participatory approaches to practice-led innovation in future strategy and policy initiatives for animal health and welfare improvement of animals. The welfare of animals kept in extensive production systems should greatly benefit from such approaches.

AUTHOR CONTRIBUTIONS

DT and XM wrote the manuscript. All authors contributed to the article and approved the submitted version.

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Ecological Implications of Plant Secondary Metabolites - Phytochemical Diversity Can Enhance Agricultural Sustainability

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Conventional agriculture production, although proficient in feeding an expanding human population, is having negative environmental impacts that are diminishing the sustainability of natural resources. Producers and consumers are increasingly interested in understanding how land management practices can enhance agricultural sustainability and improve human health. This perspective article offers a new approach to enhancing agricultural sustainability by growing crops and forages with diverse plant secondary metabolites (PSMs). Plants produce tens of thousands of PSMs to mediate interactions with soil, other plants, and animals. Plants use these metabolites to communicate with organisms in their environment, both above and belowground, and to modify the rhizosphere and influence chemical, physical, and biological attributes of soil. In pastures and rangelands, animal health benefits and production increases when animals ingest forages with different PSMs, which has implications for enhancing the biochemical richness of meat and dairy products for human consumption. A deeper understanding of PSMs, and their functional roles in agroecology, may help producers better manage their lands, reduce inputs, and minimize negative environmental impacts.

Keywords: plant secondary metabolites, sustainable agriculture, foraging animals, agroecological resiliency, ecosystem health

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INTRODUCTION

The industrialization of conventional agriculture has enhanced the proficiency of food production to support an increasing global population. Conventional crop and forage (hay or silage) production uses synthetic pesticides, herbicides, and fertilizers while conventional livestock production uses vaccines, antibiotics, medicated feeds, and growth hormones. The industrialization of conventional agriculture is the large-scale specialization of animals, crops, and forages for mass production (National Research Council, 2010). However, that has created a range of negative environmental impacts that are reducing the sustainability of agroecosystems. Conventional agriculture contributes to global greenhouse gas emissions, loss of plant biodiversity and soil organic matter, and degradation of natural resources, natural water bodies, and public health

(Bauer and Black, 1981; Nixon, 1995; Doran and Safley, 1997; Vitousek et al., 1997; National Research Council, 2010). The National Research Council (2010) compiled a list of strategies to reduce the environmental impacts of conventional agriculture including crop rotation, cover crops, reduced and/or no-tillage, integrated pest management, precision farming, diversification of farm enterprises, genetically modified crops, and agricultural conservation management practices. We offer an additional strategy to reduce the negative environmental impacts of conventional agriculture, that being, to utilize crops and forages with diverse PSMs. Using biodiverse crops and forages with different biochemistries can reduce input requirements such as pesticides and fertilizers, and reduce the need for medication and parasiticides in animal production, thus reducing negative impacts from these inputs on the environment.

Besides producing the primary compounds necessary for growth, plants produce a diverse assortment of PSMs. Research over the last several decades has illuminated the ecological significance of PSMs in defense (herbivores, fungi, bacteria, viruses, plants), attraction and stimulation (pollination, seed dispersal, symbiosis, nutrient sequestration), and protection (UV-light, evaporation, temperature extremes, drought) of plants (Hartmann, 1996; Chomel et al., 2016). These activities are accomplished through three major classes of PSMs: (1) terpenes, (2) flavonoids, phenolic and polyphenolic compounds, and (3) nitrogen-containing (i.e., alkaloids) and sulfur-containing (e.g., glucosinolates) compounds (Crozier et al., 2001).

To support our view that phytochemical diversity can enhance agricultural sustainability we begin by discussing the ecological importance of PSMs with specific examples, illustrating their role in agroecological resiliency, then we examine the value of PSMs for foraging animals. Finally, we consider how increased understanding of the various roles of PSMs in ecological systems may enhance our ability to manage agricultural lands more sustainability by reducing input requirements for both plants and animals. This view, which is new in land management, integrates plant biochemical diversity to improve agroecological resiliency and can enhance agricultural sustainability.

BENEFITS OF PLANT SECONDARY METABOLITES IN SOIL

Soil health or quality is defined as the ability of soil to sustain the life of plants and animals below and above ground while also supporting ecosystem health including air and water (Doran, 1994; Doran et al., 1996; Doran and Safley, 1997; Johnson et al., 1997; Karlen et al., 1997). Soil physical, chemical, and biological properties are interdependent. Physical structure influences biological activity, which influences chemical composition and the soil microbiome. Physical properties encompass structure, texture, porosity, and bulk density, whereas chemical properties include cation-exchange capacity, pH, salinity, macro- and micronutrients (Schoenholtz et al., 2000). Agricultural practices that diminish plant biodiversity also reduce plant biochemical diversity and degrade soil biological diversity (National Research Council, 2010; Ristok et al., 2019).

Through diverse PSMs, plants modify their environment in various ways including interactions that affect the soil microbiome in the rhizosphere, soil nutrient cycling, allelopathy, and defenses against herbivores (van Dam and Bouwmeester, 2016; Coskun et al., 2017). Plants exude certain PSMs to enhance their ability to acquire nutrients from the soil. For example, alfalfa (*Medicago sativa*) seeds and roots release flavonoids that promote the growth of *Sinorhizobium meliloti*, a N-fixing gram-negative bacterium (Hartwig et al., 1991). Under conditions of iron deficiency, some graminaceous plants (i.e., wheat, oats, barley, rye) exude mugineic acid which solubilizes iron, making it more readily available to plants (Ma and Nomoto, 1996).

Plant secondary metabolites influence soil decomposition. Tannins and terpenes affect cycling of C and N by increasing N immobilization in the soil (Bradley et al., 2000; Smolander et al., 2012). Pasture forages such as sainfoin (*Onobrychis viciifolia* Scop.), which contains condensed tannins, can inhibit soil N mineralization (Clemensen et al., 2020) and reduce N loss in pastures where N mineralization is relatively rapid. Tannins and terpenes in plant litter slow rates of nutrient cycling by supplying more recalcitrant C substrate, binding with proteins, and/or acting as toxins to soil microbes (Smolander et al., 2012), all of which inhibit N mineralization. Laboratory studies with forest soils show terpenes decrease nitrification potential and at low pH they precipitate proteins (Adamczyk et al., 2013). While terpenes can be toxic to soil microorganisms, tannins form complexes with proteins and enzymes (Hättenschwiler and Vitousek, 2000; Kraus et al., 2003; Adamczyk et al., 2011, 2019), and also form complexes with fungal compounds (i.e., *Dichomitus squalens*) (Adamczyk et al., 2019), which slows microbial decomposition processes that affect C and N cycling (Northup et al., 1995; Hättenschwiler et al., 2019). The incredibly diverse polyphenol class of PSMs is reflected in their varied influences on the soil microbial community. For instance, greater soil respiration occurs with additions of the monomeric phenol methyl gallate compared with polyphenol epigallocatechin gallate and polyphenol oenothein B (Schmidt et al., 2013). To our knowledge, research evaluating the influence of specific PSMs on soil dynamics is largely limited to forest systems, while little is known regarding these dynamics in pasture and/or cropping systems.

Root exudates contain various PSMs that can attract, deter, or kill belowground insect herbivores, nematodes, and microbes, and inhibit competing plants. Plants that exude PSMs from their roots can more easily defend themselves from below-ground injury. Plants also use these exudates to establish their spatial presence among other plant species and to communicate with other plants and animals above and belowground. For instance, in response to the root-eating larvae, *Diabrotica virgifera*, teosinte, the ancestor of wild maize and other European lines of maize, produces the volatile sesquiterpene (E)-β-caryophyllene, which attracts entomopathogenic nematodes (Rasmann et al., 2005), indirectly defending the plant against the larvae. Interestingly, newer varieties of maize in North America do not release this volatile compound as a defense mechanism (Degen et al., 2004). Alfalfa contains various saponins (triterpenes), most of which are oleananes and steroids (Kregiel et al., 2017).

Oleoresin, which has antifungal properties against *Pestalotiopsis microspora* (Chen et al., 2018), is made up of triterpenes, some of which are oleanane saponins (Liang et al., 1988). The release of flavonoids from alfalfa seeds and roots slows growth of parasitic species of *Pythium* spp. (Hartwig et al., 1991). In forest soil, terpenes, common in conifer trees, increase bacterial growth but decrease fungal growth (Adamczyk et al., 2013), yet studies exploring these dynamics in other agricultural systems is limited.

Water availability is a growing concern in agriculture. Plants respond to water stress in various ways, including increasing or decreasing primary and secondary metabolites. For example, red poppy (*Papaver somniferum)* increases concentrations of alkaloids to enhance drought tolerance (Sarker and Oba, 2018; Yang et al., 2018). Depending on the species, saponin levels decrease as some species go into reproductive phase or increase as other species age (Pecetti et al., 2006). Saponin concentrations are greater in roots than in stems, leaves, and flowers in a variety of species (e.g., *Dioscorea pseudojaponica, Polygala tenuifolia, Bupleurum chinense*, *Achyranthus bidentate*, *Gypsophilia paniculate*) (Szakiel et al., 2011), including alfalfa (Tava et al., 1993). Saponins contain both a hydrophilic and lipophilic end; thus, they can form spherical structures called micelle with negatively charged surfaces that typically do not form aggregates. However, if water solutions contain Ca+ and Mg+ ("hard" water), the micelle can form cluster aggregates, increasing water holding capacity of soil. Saponins can also reduce surface tension in aqueous solutions (Böttger et al., 2012), and by acting as surfactants they can potentially increase soil water holding capacity, thus enhancing the ability of saponin-containing plants to withstand drought.

Arbuscular mycorrhiza fungi are estimated to have formed stable relationships with roughly 80% of plant families (Smith and Read, 1997). They play major roles in soil health including protecting plants from biotic and abiotic stresses and supporting plants by releasing glomalin. Glomalin enhances the stability and water retention of soil, subsequently increasing water and nutrient uptake by plants, thus reducing fertilizer requirements (Gianinazzi et al., 2010). Additionally, arbuscular mycorrhizal fungi increase specific PSMs in plants, from 6% (methyl chavicol, a phenylpropanoid) to 697% (α-pinene, a terpene), in both field and greenhouse experiments (Kapoor et al., 2002, 2004; Gianinazzi et al., 2010), enhancing the ability of plants to adapt to different environmental circumstances.

Knowledge of PSMs can be used in land management strategies to further enhance agroecological resiliency and agricultural sustainability. For instance, tannin-containing plants such as sainfoin or birdsfoot trefoil may inhibit soil N mineralization, thus reducing N loss, while saponin-containing plants such as alfalfa may enhance soil water holding capacity.

BENEFITS OF PLANT SECONDARY METABOLITES TO PLANTS

Plant secondary metabolites offer a broad range of benefits to plants, from attracting pollinators and seed dispersers (Knudsen et al., 1993; Pichersky and Gershenzon, 2002; Bruce and Pickett, 2011; Pierik et al., 2014) to defending plants from pathogens and diseases by helping plants recover from injury (Savatin et al., 2014). Flavonoids protect plants from ultraviolet radiation (Agati and Tattini, 2010), while glycyrrhizin (a triterpene saponin) may also boost UV protection, as its production in roots increases with greater UV-B light exposure in *Glycyrrhiza uralensis* (Afreen et al., 2005). Other terpenes, the carotenoid group of tetraterpenes, more commonly known as the yellow, orange, and red pigments, likewise aid in photoprotection while also extending the range of light used in photosynthesis, regulating the effects of extreme temperatures, and protecting photosynthetic tissues from photooxidation (Strzalka et al., 2003). Phenolic compounds such as tannins may increase due to stress from UV light, heat, and/or drought (Yang et al., 2018). For example, red maple (*Acer rubrum* L.) doubles the amount of tannins in response to drought and warming (Tharayil et al., 2011), while red oak (*Quercus rubra* L.) varies both the concentration and molecular composition of tannins to better adapt to climatic stresses (Top et al., 2017).

Plant secondary metabolites are diverse in structure and function, and their production is influenced by interactions above and belowground that involve genetic, ontogenetic, morphogenetic, and biotic and abiotic factors (Verma and Shukla, 2015; Shamloo et al., 2017; Kessler and Kalske, 2018; Yang et al., 2018). Their production reflects the unique and dynamic environments plants encounter. They may increase when plants are stressed or grow in suboptimal conditions (Kamstrup et al., 2000; Yang et al., 2018). Saponins in some species peak during temperature extremes, such as hot summer and cold winter months, and decrease in spring and fall with milder temperatures, while saponins in other species may peak during the milder seasons of spring and fall (Szakiel et al., 2011). Saponin concentrations in individual soapbark trees (*Quillaja saponaria*) differ even under similar soil conditions, altitude, and age of trees suggesting genetics play a role in the production of PSMs (Kamstrup et al., 2000).

Chemical responses within plants are genetically derived and environmentally induced, and thus can differ between and within species, and among different tissues in a plant (Macel et al., 2010; Verma and Shukla, 2015). Depending on the plant species, and specific secondary metabolite, some PSMs are produced and then stored in tissues (e.g., tannins) while others are produced *de novo* in response to environmental perturbations (e.g., various monoterpenes and alkaloids). These metabolites are concentrated in particular plant cells or tissues, restricted to particular developmental stages of growth, and transferred "long distances" within plants via the xylem and/or phloem or "short distances" via translocation between cells (Hartmann, 1996).

Plants also release various volatile compounds to interact with their environment (Pichersky and Gershenzon, 2002; Laothawornkitkul et al., 2009; Baldwin, 2010). Most of these compounds are terpenoids that may be emitted differently depending on circadian rhythms. Volatile compounds can attract or deter pollinators, and they also play vital roles in direct and indirect defenses for plants (Turlings et al., 1995; Kessler and Baldwin, 2001; Pichersky and Gershenzon, 2002). For instance, when the tobacco plant (*Nicotina attenuata* Torr. ex

Wats.) is attacked by the tobacco hornworm (*Manduca sexta* L.), a nicotine-tolerant folivore, the plant suppresses its typical folivore-induced increase in nicotine production (Baldwin, 1988), and instead emits an assortment of volatile organic compounds [(E)-α-bergamotene] that attract the generalist predator *Geocoris pallens* as a defense against *Manduca* (Kessler and Baldwin, 2001; Halitschke et al., 2007; Zhou et al., 2017). Plants naturally produce insecticides that may negate the need for synthetic insecticide applications if crop and forage varieties are selected and managed to increase production of these PSMs. For example, the alkaloid nicotine deters herbivores so effectively (Steppuhn et al., 2004) it has been used commercially as an insecticide (Soloway, 1976). Other insecticidal PSMs include pyrethrins (Xu et al., 2018), and the triterpene azadirachtin, found in citrus (limonoids), which is non-toxic to plants and animals yet is a strong insect deterrent (Aerts and Mordue Luntz, 1997). Natural biochemicals such as pyrethroids have been used to create synthetic insecticides due to their effectiveness at deterring insects, their evanescence in the environment, and their minimal impact to mammals.

Rarely does one secondary metabolite enable plants to cope with environmental challenges. Rather, plants rely on combinations of different metabolites (Gershenzon and Dudareva, 2007). Plant volatiles are typically emitted in blended "bouquets" (Baldwin, 2010) that have layered functions of attractants or deterrents. Badenes-Perez et al. (2014) found a positive correlation between the feeding deterrents glucosinolate (a sulfur-containing compound) and saponins (triterpenes) for insects consuming Brassicaceae species.

The production of PSMs is a crucial way that plants interact within their social and biophysical environments. In our view, strategic management and utilization of plant phytochemical diversity may improve agricultural sustainability and resiliency while reducing input requirements. As we discuss next, at appropriate doses PSMs add health benefits for consumption by herbivores and humans (Provenza et al., 2019).

IMPACT OF PLANT SECONDARY METABOLITES ON FORAGING ANIMALS

Some PSMs are well known for their poisonous potential to animals, and herbivores respond by reducing their intake of plants containing PSMs as a function of the concentration of the metabolites in plants (Provenza et al., 2002, 2003). As Paracelsus (1493–1541) wrote, "All substances are poisons; there is none which is not a poison. The right dose differentiates a poison from a remedy."

Plant secondary metabolites, namely alkaloids, can be toxic to ruminants (Stidham et al., 1982; Rhodes et al., 1991; Aldrich et al., 1993; Thompson et al., 2001). However, by offering animals either supplements (Mantz et al., 2008; Bernard et al., 2013; Jensen et al., 2014), or diverse forages containing different PSMs (Lyman et al., 2008, 2011, 2012; Owens et al., 2012a,b), biochemical complementarities can reduce the negative effects of alkaloids in plants like endophyte-infected tall fescue (*Schedonorus arundinaceus*) and terpenes in plants like sagebrush (*Artemisia tridentata*), either by binding or through other mechanisms (Freeland et al., 1985; Charlton et al., 2000; Seefeldt, 2005; Mote et al., 2008; Catanese et al., 2014; Clemensen et al., 2017).

Phenolic compounds have antioxidative and anticarcinogenic benefits that also aid digestion (Waghorn et al., 1994; Waghorn, 2008). Condensed tannins reduce internal parasites and nematodes in ruminants and, due to their protein-binding characteristics, also enhance the absorption of amino acids in the small intestine, analogous to by-pass proteins popular in ruminant nutrition (Barry and McNabb, 1999; Villalba et al., 2013). Like tannins, saponins can precipitate proteins (Livingston et al., 1979), while lowering cholesterol in animals (Aazami et al., 2013). Saponins may improve growth and feed efficiency, reduce protozoa in the rumen, and increase efficiency of rumen-microbial protein synthesis (Francis et al., 2002).

The emphasis on planting monocultures, combined with the influence of PSMs on reducing intake of any one forage, is why these metabolites have historically been bred out of plants used for crops and forages (Wink, 1988; Jacobsen, 1998; Provenza et al., 2007). Foraging animals eat more and perform better when offered a variety of forages with different kinds and amounts of PSMs (Provenza, 1996; Provenza et al., 2007, 2009), which at appropriate doses offer numerous health benefits to foraging animals (Engel, 2002; Cheeke et al., 2006; Provenza and Villalba, 2010; Meuret and Provenza, 2015). Historically, researchers and producers have focused on the three to five species which contribute the most to intake of energy and protein for livestock, but animals will eat an additional 50–75 species in a meal. These 50–75 other plant species are equally, if not more important for the health of livestock and humans through the meat and dairy products we derive from them (Provenza et al., 2019).

PLANT SECONDARY METABOLITES, HERBIVORES, AND HUMAN HEALTH

In addition to improving the health of foraging animals, ingesting various PSMs enhances the phytochemical and biochemical richness, flavor, and quality of cheese, milk, and meat for human consumption (Vasta et al., 2008; Vasta and Luciano, 2011; Maughan et al., 2014; Provenza et al., 2019). Our health is thus linked with the diets of livestock through the chemical characteristics of the plant species they eat. Through their anti-inflammatory, immunomodulatory, antioxidant, anti-bacterial, and anti-parasitic properties, phytochemicals in plants protect livestock and humans against diseases and pathogens (Provenza, 2018). The benefits of eating meat to humans accrue as livestock convert rich arrays of phytochemicals into biochemicals that are incorporated into their meat and fat, which in turn become healthy biochemicals in human bodies, similar to the benefits attained by eating phytochemically rich herbs, spices, vegetables, and fruits (Provenza et al., 2019). Those compounds may confer the same benefits to us as to livestock, dampening oxidative stress and inflammation linked with cancer, cardiovascular disease, and metabolic syndrome.

Historically, plants were the source of medicine for all animals, including humans. Today, various drugs (antibiotics, pain killers, fever reducers, etc.) are derived from plants that produce these chemicals naturally. Several reviews describe the many health promoting properties of PSMs to animals, including humans (Verpoorte, 1998; Craig, 1999; Bourgaud et al., 2001; Maganha et al., 2010; Kabera et al., 2014). The opportunity is to reconsider the fundamentally important roles these compounds played in health before the advent of modern medicine (Provenza, 2018), while integrating plants with diverse PSMs back into our crops and forages.

PLANT DIVERSITY IN AGRICULTURAL SYSTEMS

Over the past 50 years, we have simultaneously come to better understand the roles of PSMs in protecting plants against herbivores, pathogens, and competition, while reducing their concentrations in crop and pasture plants to maximize yields. In their stead, cultivation and synthetic chemicals have been used to protect plants grown in monocultures. With good intentions to feed an exponentially growing human population, the simplification of agricultural systems has produced various negative impacts too numerous to overlook (Foley, 2005; Hendrickson et al., 2008; Hendrickson and Colazo, 2019), resulting in a need for change.

Increasing plant diversity in agricultural systems offers ecosystem benefits from the soil, to plants and animals, to the atmosphere, enhancing agroecological sustainability. Belowground, PSMs defend against root-eating larvae while also influencing nutrient cycling as carbonaceous metabolites such as tannins and terpenes slow mineralization in the soil, potentially increasing soil microbial biomass, thus increasing carbon sequestration potential in agriculture soil. Aboveground, PSMs aid plants and act as insecticides when defoliation pressure develops. Diverse plant species with differing PSMs enhance balanced eating habits while also offering health benefits to herbivores and humans (Provenza et al., 2007). Further, methane emissions are reduced when cattle graze forages containing tannins (Pinares-PatiñO et al., 2003; Boadi et al., 2004; Woodward et al., 2004; Beauchemin et al., 2007; Jayanegara et al., 2009). Thus, planting forages containing different PSMs may reduce greenhouse gasses by influencing rumen fermentation and soil mineralization (Goel and Makkar, 2012; Provenza et al., 2019).

We have emphasized growth of crops and livestock, at the expense of phytochemical richness, through the varieties we have selected and the management practices we have used, including applications of water and fertilizer to enhance growth, and pesticides to prevent herbivory by insects. Alternatively, stressing plants by reducing inputs of fertilizers, insecticides, and water can increase production of PSMs, which typically increase with various environmental stressors (Shamloo et al., 2017; Yang et al., 2018; Roberts and Mattoo, 2019). However, research is needed to further explore how stress via reduced inputs may influence the biosynthesis of PSMs in crops and forages. A deeper understanding of PSMs, and their functional roles in agroecology, may help producers better manage their lands, reduce inputs, and minimize negative environmental impacts.

We have discussed qualitative aspects of PSMs in enhancing agricultural sustainability. We have not mentioned the quantification of these metabolites. Quantifying PSMs in any system is challenging, as each species differs in production between root and shoot tissues with varying circumstances. Thus, it is difficult to quantify how much of any specific PSM enters a system (i.e., Kraus et al., 2003). Recent results suggest that the concentration of tannins in cattle feces is proportional to the concentration of tannins in the forage consumed (Stewart et al., 2019). Models must consider concentrations of PSMs in plant tissues, as well as PSMs exuded from roots, and residual PSMs in decomposing plant matter. Further, the analytical procedures for extracting and quantifying PSMs is labor intensive and typically requires substantial quantities of laboratory chemicals. Thus, a need for developing more efficient methods of analysis is essential. Additional research opportunities exist in evaluating which crops and forages may contain optimal PSMs to reach land management objectives.

It is ironic that we have selected against PSMs in crop and pasture plants that we are now intent on genetically engineering back into plants (Provenza et al., 2007). Enhancing plant biodiversity and associated phytochemical diversity offers a logical progression to improve agricultural resilience while providing ecosystem services that also benefit the health of herbivores and humans.

AUTHOR'S NOTE

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All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Health-Promoting Phytonutrients Are Higher in Grass-Fed Meat and Milk

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While commission reports and nutritional guidelines raise concerns about the effects of consuming red meat on human health, the impacts of how livestock are raised and finished on consumer health are generally ignored. Meat and milk, irrespective of rearing practices, provide many essential nutrients including bioavailable protein, zinc, iron, selenium, calcium, and/or B_{12}. Emerging data indicate that when livestock are eating a diverse array of plants on pasture, additional health-promoting phytonutrients—terpenoids, phenols, carotenoids, and anti-oxidants—become concentrated in their meat and milk. Several phytochemicals found in grass-fed meat and milk are in quantities comparable to those found in plant foods known to have anti-inflammatory, anti-carcinogenic, and cardioprotective effects. As meat and milk are often not considered as sources of phytochemicals, their presence has remained largely underappreciated in discussions of nutritional differences between feedlot-fed (grain-fed) and pasture-finished (grass-fed) meat and dairy, which have predominantly centered around the ω-3 fatty acids and conjugated linoleic acid. Grazing livestock on plant-species diverse pastures concentrates a wider variety and higher amounts of phytochemicals in meat and milk compared to grazing monoculture pastures, while phytochemicals are further reduced or absent in meat and milk of grain-fed animals. The co-evolution of plants and herbivores has led to plants/crops being more productive when grazed in accordance with agroecological principles. The increased phytochemical richness of productive vegetation has potential to improve the health of animals and upscale these nutrients to also benefit human health. Several studies have found increased anti-oxidant activity in meat and milk of grass-fed vs. grain-fed animals. Only a handful of studies have investigated the effects of grass-fed meat and dairy consumption on human health and show potential for anti-inflammatory effects and improved lipoprotein profiles. However, current knowledge does not allow for direct linking of livestock production practices to human health. Future research should systematically assess linkages between the phytochemical richness of livestock diets, the nutrient density of animal foods, and subsequent effects on human metabolic health. This is important given current societal concerns about red meat consumption and human health. Addressing this research gap will require greater collaborative efforts from the fields of agriculture and medicine.

Keywords: meat, milk, phytochemicals, organic, grass-fed, health, sustainability, nutrition

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INTRODUCTION

Navigating discussions on red meat and human and environmental health are challenging. On the one hand, reports such as those by the EAT-Lancet Commission asks consumers to embrace near plant-exclusive diets to reduce our impacts on planetary health (Willett et al., 2019). On the other hand, reports such as those by the United Nations Intergovernmental Panel on Climate Change (IPCC, 2019) suggest a critical role for sustainable livestock production systems in climate change mitigation by integrating tree, crop, and livestock production systems, while ensuring global food security and nutrient adequacy via consumption of moderate amounts of animal foods.

Meanwhile in the field of human nutrition, a wealth of epidemiological data associate animal food consumption, particularly red meat, with increased risk of cancer (Chan et al., 2011), cardiovascular disease (Zhong et al., 2020), obesity (Wang and Beydoun, 2009), and diabetes (Micha et al., 2012). This has led to widescale public health recommendations by the American Heart Association (Arnett et al., 2019), the World Health Organization (Bouvard et al., 2015), and the Dietary Guidelines for Americans (USDA, 2015) to reduce red meat consumption in an effort to halt metabolic disease. However, these recommendations have been challenged by the NutriRECS consortium, as scrutinizing the data with the GRADE (Grading of Recommendations, Assessment, Development, and Evaluations) system resulted in considerable uncertainty regarding the robustness of evidence associating consumption of red meat with increased risk of metabolic disease (Johnston et al., 2019).

While public health experts and climate scientists argue about whether we should rely on livestock production systems to meet the nutritional demands of a growing global population while tackling climate change, those who produce our food—the "average" farmer—are struggling financially (Wiggins et al., 2010). To make a decent living, farmers must balance trade-offs between land ecology, animal welfare, and profitability, which in modern-day farming practices are not necessarily in agreement with each other. High costs for inputs, but low income from farming, has created depression and suicide rates well-above national averages amongst farmers in the US, New Zealand, Australia, and Europe (Klingelschmidt et al., 2018).

Yet some farmers have costs of production much less than the national average and are able to cut costs, and thereby increase the profitability of their operations (Provenza, 2008). Increased consumer demand for (local) grass-fed meat and milk have encouraged a number of producers to implement farming practices many describe as regenerative agriculture (i.e., farming in harmony with agroecological principles). As some farmers have learned, they are able to cut costs and increase profits by focusing on reducing inputs such as water, fertilizer, concentrate feeds, and herbicides; by raising multiple species of livestock on diverse assemblages of cover crops and/or perennial plants; and by selling their meat and milk directly to consumers (Massey, 2017; Brown, 2018).

Pasture-based grazing systems, when managed in ways that mimic natural ecosystems, can improve plant diversity (Teague, 2018), soil carbon levels (Allard et al., 2007; Stanley et al., 2018), ecosystem function (Krausman et al., 2009; Teague and Kreuter, 2020), and water retention and quality of fresh water systems (Park et al., 2017). As the IPCC (2019) notes, Earth's health depends upon plant diversity and abundance, which can be improved by managing the grazing behavior of livestock when done in concert with agroecological principles (i.e., that mimic natural processes). That should come as no surprise in the light of plant-herbivore coevolution, which have evolved to form complex reciprocal relationships over millions of years.

The constant "arms race" between plants and herbivores has resulted in an extraordinary diversity of phytochemicals produced by plants (Burkepile and Parker, 2017). In turn, many of these plant phytochemicals are concentrated in the meat and milk of livestock grazing these plants (Børge et al., 2016; Delgadillo-Puga et al., 2019; Prache et al., 2020); their presence may act synergistically to enhance human health (Barabási et al., 2020). Importantly, the presence of these phytochemicals in pasture-raised animal products remains largely underappreciated in discussions of nutritional differences between grain-fed and pasture-raised (grass-fed) meat and dairy, which have predominantly been centered around the ω-3 fatty acids and CLA (Provenza et al., 2019). In this review, we discuss the information currently available on the wide range on phytochemicals found in grass-fed meat and dairy products and evaluate their potential health effects.

WHY BECOMING LOCALLY ADAPTED MATTERS

Natural landscapes are diverse mixtures of plants that occur in patches reflecting history of use in concert with particular soil, precipitation, and temperature regimes. Plants are nutrition centers and pharmacies with vast arrays of primary (e.g., protein, fiber, carbohydrates, fats, vitamins, and minerals) and secondary compounds (e.g., phenols, terpenoids, anti-oxidants, organic acids, and other phytochemicals) useful in both animal (Craig, 1999; Poutaraud et al., 2017) and human health (Kris-Etherton et al., 2002; Chadwick et al., 2013; Kim, 2016).

Of roughly 200,000 species of wild plants on earth, only a few thousand are eaten by humans, just a few hundred of these have been domesticated, and only a dozen account for over 80% of the current annual production of all crops (FAO, 2010). By focusing on a few species, people transformed the diverse world of plants into a manageable domain that generally met needs for nutrients, mainly energy, while limiting over-ingestion of toxins (Johns, 1994). In so doing, however, we narrowed the genetic basis of crop production to just a few plants, relatively productive in a broad range of environments, rather than broadening the range of plants that are valuable in local environments (Shelef et al., 2017). We have also discovered only a fraction of the plant mixtures useful in nutrition and health (Etkin, 2000) and we have simplified agricultural systems in ways that are having alarming consequences on the health of people and the planet (Provenza, 2018). Though often successful in the short term, "simplifying" ecosystems can lead to ruinous long-term impacts, as shown in marine, forest, and rangeland systems (Gunderson et al., 1995). By maximizing the output of one component of a system, we inevitably hasten the demise of ecosystems.

The United Nations Commission on Genetic Resources for Food and Agriculture has declared the loss of biodiversity as one of the major threats to the productivity and resilience of food production systems (Pilling et al., 2020). Biodiversity amongst soil microorganisms, plants, and animals, which have co-evolved to form complex symbiotic relationships over millions of years, are essential to maintain soil health and sustainable agroecosystems (Coleman and Whitman, 2005; De Faccio Carvalho et al., 2010). The structural and functional diversity inherent in natural systems increases productivity of plant and animal species, and enhances system resilience. Studies of natural systems highlight the benefits of plant and animal biodiversity for reducing inter-annual variability in production and minimizing risk of large-scale catastrophic events, such as wildfire and outbreaks of diseases and pests (Gunderson et al., 1995; Provenza et al., 2007). Diversity in terms of nutrition also increases the range of options available for both animals and humans to nourish themselves and medicate prophylactically.

Along with reductions in per capita meat consumption in industrialized nations (Godfray et al., 2018), meat consumption will arguably need to increase in developing nations to meet basic needs for protein, essential fatty acids, and micronutrients (Adesogan et al., 2019). It was recently estimated that animal-sourced food consumption at $^1/_3$ of total energy intake (i.e., a 1:2 energy intake ratio of animal to plant foods) will provide nutritionally adequate diets for most of the global population (Nordhagen et al., 2020), a target currently not met in the majority of low-to-middle income countries (FAO, 2020). By including complementary nutrient-dense plant foods (Eshel et al., 2019), and depending on intra-individual differences in nutrient metabolism (Brenna, 2002; Stover and Caudill, 2008; Tang, 2010; Engelken et al., 2014), even lower amounts of animal sources foods may be sufficient to achieve nutrient adequacy in certain individuals within the population. That is more feasible in high-income than low-income countries as a result of food availability (FAO, 2020).

Beyond meeting basic nutrient requirements, people in low-income countries often depend on livestock rearing not just for food, but for their entire livelihood; at the household level, livestock contribute 68% of income in low- to middle-income households (FAO, 2009). For the poorest, grazing livestock is an effective way to reduce poverty (Omamo et al., 2006) from the sale of excess foodstuff, fiber, and waste products, especially when livestock are managed in ways that sustain the natural resource base (e.g., increase soil organic carbon content, reduce soil erosion, and integrate crop-livestock systems) (IPCC, 2019). Importantly, 3.4 billion hectares (70% of current agricultural land) of land will support livestock and wild animals, but not crop production (FAOSTAT, 2020). That is significant because the majority of those lands are in developing nations and are home to billions of people who depend on livestock grazing for their livelihood.

As ecological, economic, and human health concerns mount—soil, water, and climate change; animal welfare; and red meat consumption and human health—demand for livestock reared on pasture will further increase in both developing and developed nations. For example, the US grass-fed beef market increased from $17 million in retail sales in 2012 to $480 million in 2019, and this trend is expected to continue in the years ahead (Nielsen, 2020). Moreover, the organic dairy market is expected to register a compound annual growth rate of 10% in the next 5 years (Kumar and Deshmukh, 2019). The challenges and opportunities are to create grazing-based livestock-production systems based on phytochemically diverse forages for specific ecoregions at temporal and spatial scales that enhance livestock production, ecological services, and animal and human health (Gregorini et al., 2017; Provenza et al., 2019).

While understanding animal adaptations to landscapes has always been an important aspect of nutritional ecology (Demment and Van Soest, 1985), until recently land managers have not attempted to put these ideas into practice on a wide-scale. We often consider cattle to be grass eaters and sheep to be forb eaters; however, they can thrive under a wide range of conditions, including shrub-dominated areas in the arid southwest US (Provenza and Balph, 1990), high-altitude pastures in the Alps (Verrier et al., 2005), and the Amazon rainforest (Loker, 1994), provided they have been selected anatomically, physiologically, and behaviorally to survive on their own in the landscapes they inhabit, and are compatible with wildlife inhabiting these environments (Provenza, 2008).

Offering locally-adapted animals choices on pastures and rangelands also allows each individual to meet its needs for nutrients and to regulate its intake of secondary compounds by mixing foods in ways that work for that individual (Provenza et al., 2003). Cattle, sheep, and goats eat more and perform better when they are offered a wide variety of plants that contain secondary compounds (Provenza et al., 2007). Variety is so important that bodies have built-in mechanisms to ensure animals eat a variety of foods and forage in different locations to satiate and meet nutritional requirements (Bailey et al., 1996; Provenza, 1996). Thus, variety not only enables individuality, it also greatly increases the likelihood of providing cells with the vast arrays of primary and secondary compounds essential for their nutrition and health. While we often do not think of animals as intelligent beings; animals, unlike humans, do not have to be told what to eat and nurture themselves prophylactically—to prevent disease—and medicinally—to treat disease (Provenza, 2008).

Livestock are intelligent beings (Marino and Allen, 2017); they possess most of the mental, emotional, and behavioral traits we identify in humans, and by nurturing livestock we can nurture ourselves (Provenza et al., 2019). During the Green Revolution (1950-60s), agricultural systems largely moved away from integrated multi-species livestock-crop systems toward farming systems where livestock are separated from plant farming, and finished (cattle and sheep) or raised almost exclusively (poultry and pigs) in concentrated operations where animals are fed total mixed rations. Depending on practices, confined feeding systems can thwart the animals' ability to self-select their own diet and express natural behavior, which can adversely affect their welfare and health.

For example, Carrillo et al. (2016) found increased blood glucose and cortisol levels in feedlot-finished vs. pasture-raised cattle, which indicates impaired metabolic health and increased stress in the feedlot-fed animals. Metabolomic and gene expression analyses also revealed mitochondrial dysfunction and impaired oxidative phosphorylation in muscle tissue of feedlot-finished cattle. These findings were corroborated by a recent report demonstrating that meat of grass-fed animals displays a phenotype of improved oxidative metabolism compared to meat from feedlot-finished animals (Apaoblaza et al., 2020). This is consistent with studies of lambs, who display similar elevations in blood cortisol and behavioral changes indicative of stress and fear when fed total-mixed rations, formulated for the "average lamb," compared to having a broader dietary choice (Catanese et al., 2013).

Importantly, the metabolic phenotype of the feedlot-finished animals described in the work by Carrillo et al. (2016) and Apaoblaza et al. (2020) shows similarity with the human phenotype of metabolic disease, which is also characterized by muscle mitochondrial dysfunction (Nisoli et al., 2007), increased oxidative stress (Whaley-Connell et al., 2011), and elevated blood glucose (Grundy et al., 2004) and cortisol (Rosmond, 2005). In contrast, the greater mitochondrial oxidative enzyme content in pasture-raised animals (Apaoblaza et al., 2020) can be considered that of a healthy athletic phenotype. Certainly, animal health issues can also arise in ill-managed pasture-based systems. While causality cannot be inferred from these data, the link between consuming meat and dairy products from animals—that display varying degrees of metabolic health—and the subsequent effects on human metabolic health requires further examination.

LINKING LIVESTOCK SYSTEMS TO HUMAN HEALTH

Several studies associate red meat, and to a lesser extent dairy, with an increased risk of cardiovascular disease (Kaluza et al., 2012; Ding et al., 2019), cancer (Ganmaa et al., 2002; Chan et al., 2011; Fraser et al., 2020), type II diabetes (Pan et al., 2011), and early mortality (Schwingshackl et al., 2017b; Zheng et al., 2019). However, associations between red meat and increased disease risk are not supported by several other studies, especially when dietary quality is high (i.e., diets rich in fruits/vegetables and low in ultra-processed foods) (Schulze et al., 2003; Kappeler et al., 2013; Grosso et al., 2017; Maximova et al., 2020). In the case of dairy, higher intakes are often also found to be neutral or even protective (Aune et al., 2012; Guo et al., 2017; Schwingshackl et al., 2017a). Regardless of the directionality of associations and potential nuances of residual confounding in associative data, currently available epidemiological data do not differentiate among ways that livestock are raised and finished (on pasture or feedlots) nor do epidemiological studies often discriminate different types of red meat (e.g., beef, pork, or lamb) and dairy (e.g., cow, goat, or sheep) that people consume (Provenza et al., 2019).

To determine whether livestock rearing practices modulate health associations, we encourage epidemiological studies to include questions regarding sourcing of meat and dairy (e.g., grass-fed, pasture-raised, organic, "conventional" [no designation on package] etc.) on self-reported dietary recalls and Food Frequency Questionnaires. A potential caveat is that those who buy more pasture-raised meat and dairy are more health-conscious to begin with (Ziehl et al., 2005), highlighting a need to account for both lifestyles and individual diets in studies comparing health associations with meat consumption from different livestock production systems (e.g., pasture-raised, grass-fed vs. grain-fed).

Meat and milk consumption, irrespective of rearing practices, substantially contribute to many essential nutrients in the human diet including protein, zinc, selenium, iron, phosphorus, calcium, and vitamins B_{12} and D (Phillips et al., 2015; De Gavelle et al., 2018). While little difference exists in total protein content between pasture-raised and feedlot-finished meat and dairy (Duckett et al., 2009; Schönfeldt et al., 2012), differences do exist in vitamins and trace minerals. For example, Duckett et al. (2009) compared riboflavin and thiamine in grass-finished vs. grain-finished beef, and found nearly 2-fold higher riboflavin concentrations and 3-fold higher thiamine concentrations in grass-finished beef. Pasture-raised meat and dairy also have more favorable fatty acid compositions compared to their feedlot-fed counterparts (Daley et al., 2010; Benbrook et al., 2018). Pasture-raised meat and dairy is generally lower in saturated fat and cholesterol, and contains more conjugated linoleic acid (CLA) and ω-3 fatty acids compared to feedlot-finished counterparts (Bergamo et al., 2003; Daley et al., 2010; Villeneuve et al., 2013; Coppa et al., 2019). It is often stated that ω-3 fatty acids are present in such modest amounts in pasture-raised beef that any difference between pasture-raised vs. feedlot-fed beef is not of biological relevance. This is arguably the case for the ω-3 fatty acids docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), which have been studied extensively for their ability to lower metabolic disease risk (Kris-Etherton et al., 2003; Calder, 2010). This notion, however, fails to take into account the abundance of the ω-3 fatty acid docosapentaenoic acid (DPA) in pasture-raised beef, which can effectively be converted to EPA *in vivo* in humans (Miller et al., 2013), and may exert anti-inflammatory effects on its own (Dalli et al., 2013). Eating pasture-raised beef increased blood levels of DPA and EPA concentrations of humans, while no such effects were observed with feedlot-finished beef (McAfee et al., 2011).

Dairy and meat from pasture-raised ruminants are also rich sources of conjugated linoleic acids (CLA). CLA refers to a family of geometric and positional isomers of 18-carbon linoleic acids that are produced by bacterial biohydrogenation of forage in the rumen or through subsequent δ-9-desaturase enzymatic conversion of trans-vaccenic acid (TVA) in the mammary gland and/or adipose tissue (Jahreis et al., 1997). While humans can also produce certain isomers of CLA *in vivo* through δ-9-desaturase conversion of TVA (Kuhnt et al., 2006), this conversion is so low that meat and milk represent the main sources of CLA for humans (Adlof et al., 2000).

CLA is predominantly studied for its anti-carcinogenic and anti-adipogenic properties. For instance, consumption of CLA-rich butter reduced cancer proliferation in animal models of breast cancer (Ip et al., 1999). In addition, dietary intake of CLA and serum concentrations of CLA are inversely related to risk of breast cancer and colorectal cancer in some (Aro et al., 2000; Larsson et al., 2005), but not all (Norris et al., 2009), population-based studies. Several studies find that the CLA content is 1.5 and 3 times times higher in pasture-raised meat and dairy, respectively, than grain-fed products (Dhiman et al., 1999; Daley et al., 2010; Benbrook et al., 2018), an outcome believed to be due to a more favorable rumen pH as a result of forage- as opposed to grain-feeding (Bessa et al., 2000). Unsurprisingly, consuming pasture-raised animal products elevates serum CLA concentrations in humans compared to grain-fed animals (Ritzenthaler et al., 2005; Brown et al., 2011).

While improved fatty acid ratios (ω-3: ω-6) and CLA have been the predominant focus in comparisons of pasture-raised, grass-fed vs. grain-fed meat and milk, emerging data indicate that when livestock are eating a diverse array of plants on pasture, many plant phytochemicals are also concentrated in their meat and milk (Prache et al., 2005; Carrillo et al., 2016). This is noteworthy as phytochemicals are often considered to occur only in plant foods.

PHYTOCHEMICALS IN MEAT AND MILK

Terpenoids

Terpenoids—monoterpenes, diterpenes, and sesquiterpenes—are a large and diverse class of phytochemicals studied extensively for their anti-inflammatory, anti-oxidant, anti-viral, and anti-carcinogenic properties (Zhang et al., 2005; Merfort, 2011; Chadwick et al., 2013). The presence of terpenoids in animal foods is directly related to the terpenoid composition of the animal's diet (Vialloninsta et al., 2000; Bugaud et al., 2001; Priolo et al., 2003). Animals grazing more botanically diverse pastures accumulate both higher amounts and a wider variety of terpenoids (and other phytochemicals) in their meat and milk compared to animals grazing non-diverse (i.e., monoculture) pastures, while concentrations of phytochemicals are further reduced—and often remain undetected—in the meat and milk of animals fed grain-based diets in feedlots (**Figure 1**).

Milk obtained from cattle grazing diversified forages contained 6 to 23 times more monoterpenes (α-thujene, camphene, o-cymene) and sesquiterpenes (α-copaene, ß-caryophyllene) than milk obtained from animals fed concentrates (Martin et al., 2005). Similarly, Agabriel et al. (2007) found that terpenes—such as α-copaene (anti-oxidant), β-bourbonene (anti-tumor, apoptosis inducer), β-pinene (anti-inflammatory, anti-oxidant, anti-tumor), β-Elemene (anti-inflammatory, anti-tumor), and sabinene (anti-inflammatory, anti-oxidant)—were higher in milk from pasture-raised animals with access to more forage diversity compared to animals fed grain-based diets. Likewise, Børge et al. (2016) found that δ-3 Carene, α + β-pinene, α-thujene, ß-citronellene, and sabinene concentrations (anti-inflammatory, anti-bacterial, anti-oxidant, and/or anti-carcinogenic) were collectively 5-fold higher in cream produced from animals raised on diversified pasture compared to cream from animals fed concentrates.

Amongst pasture-based systems, greater botanical diversity of forage generally results in higher terpenoid concentrations in meat and milk. For example, goats grazing a wide variety grasses, legumes, and forbs concentrated 5-fold more terpenoids in their milk compared to goats consuming a limited number of grasses (alfalfa, perennial rye grass, and orchard grass) (Fedele et al., 2007). Similar findings were made by Martin et al. (2005) who found that milk samples from cattle grazing diversified mountain pastures were enriched in terpenoids compared to cattle grazing a ryegrass monoculture. While the presence of terpenoids have predominantly been studied in dairy systems, higher concentrations of terpenoids have also been found in the meat of grass-fed cattle (Larick et al., 1987) and lambs (Priolo et al., 2003) compared to their grain-finished counterparts (**Table 1**).

Besides differences in pasture diversity, seasonality also impacts the terpenoid content of milk with highest concentrations observed during the summer, compared to the fall and spring, while concentrations are lowest during the winter (Agabriel et al., 2007; Chion et al., 2010; Valdivielso et al., 2017). These findings can be ascribed to the differences in cattle diets (fresh pasture vs. hay) (Valdivielso et al., 2017) and/or seasonal differences in terpenoid content of grazed plants (Mariaca et al., 1997). These differences can be substantial, as demonstrated by Valdivielso et al. (2017), who found that terpenoids were 5-fold higher in the summer compared to the winter, and 2-fold higher in the summer compared to the spring. Even during winter, when terpenoids concentrations in pasture-fed milk were lowest, concentrations remained 2-fold higher for pasture-fed compared to grain-fed animals, which obviously experience little seasonality due to largely standardized total-mixed ration feeding throughout the year (Agabriel et al., 2007).

Phenols

Phenols in plants exert strong *in vivo* anti-oxidative and anti-inflammatory effects in both animals (Poutaraud et al., 2017) and humans (Zhang and Tsao, 2016). Phenols consist of one (phenolic acids) or more (polyphenols) aromatic rings with attached hydroxyl groups as part of their structures (Lewandowska et al., 2013). Therapeutic benefits of phenols include protection again various cancers (Kampa et al., 2007; Zhou et al., 2016), hepatic disorders (Saha et al., 2019), cardiovascular disease (Khurana et al., 2013), neurodegenerative diseases (Vauzour, 2012), type 2 diabetes (Guasch-Ferré et al., 2017), obesity (Wang et al., 2014), improved immune function (Ding et al., 2018), and gut microbial composition (Cardona et al., 2013).

Similar to terpenoids, the presence of phenols in milk is directly related to the phenolic composition in the diet (De Feo et al., 2006; Besle et al., 2010; Di Trana et al., 2015), with higher concentrations observed during summer compared to winter (Cabiddu et al., 2019), and higher concentrations in meat and milk from animals fed a botanically diverse diet on pasture compared to animals raised on monoculture

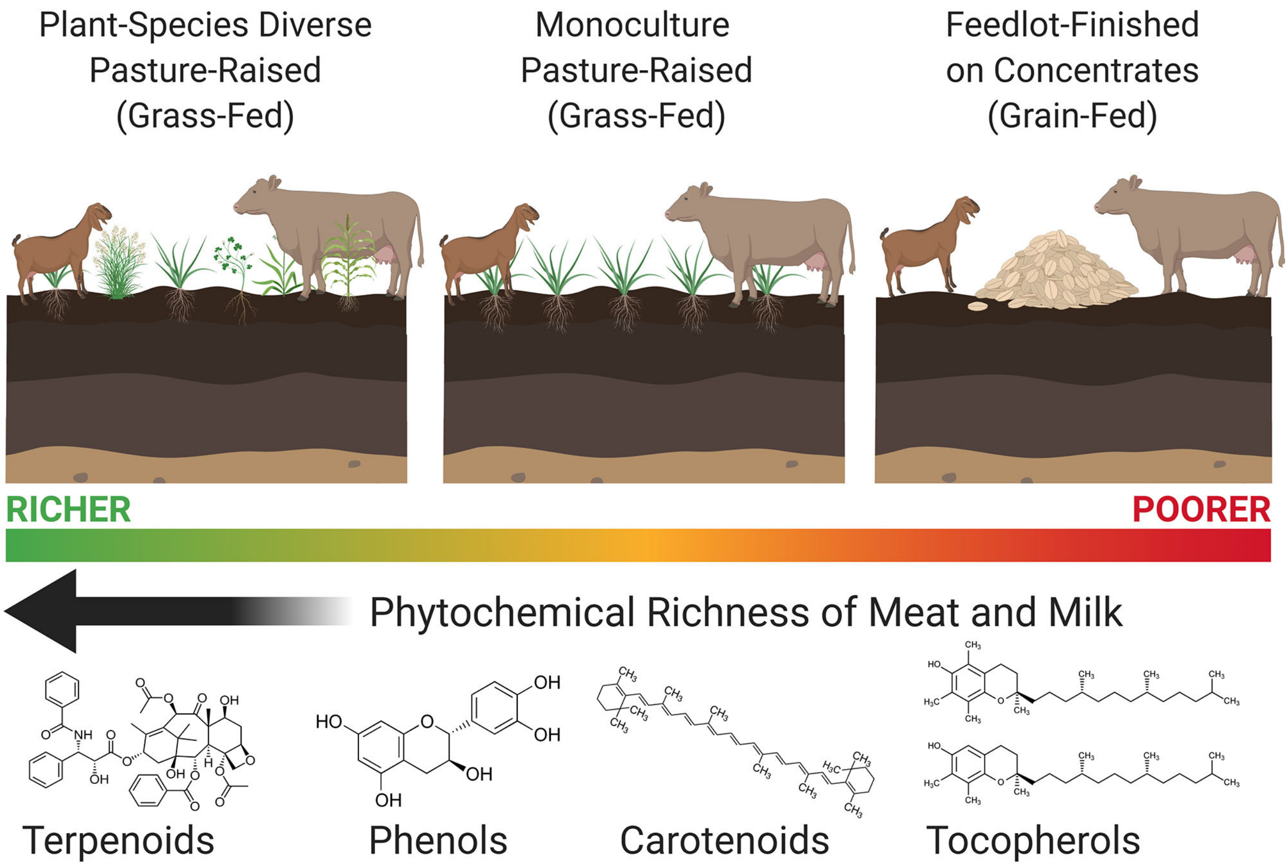

FIGURE 1 | The effects of livestock production systems on the phytochemical richness—terpenoids, phenols, carotenoids, and tocopherols—of meat and milk. Grazing livestock on plant-species diverse pastures concentrates a wider variety of phytochemicals in their meat and milk compared to animals grazing non-diverse pastures, while phytochemicals are further reduced and often remain absent in meat and milk from animals fed grain-based concentrates in feedlots. Created with BioRender.com.

pastures, with lowest concentrations found in animals fed grain-based concentrates (**Table 1**). For example, flavonoid and caffeoylquinic acid content is 6-fold higher in milk from cattle raised on botanically-diverse mountain pastures compared to cattle raised on monoculture grasses, and is largely undetected in milk from animals fed concentrates in confinement (Besle et al., 2004, 2010). In these studies, concentrations of phenols showed a clear stepwise increase as botanical diversity of forage increased (grassland pasture > grassland hay > ryegrass hay > ryegrass silage > concentrates). Likewise, Delgadillo-Puga et al. (2019) found that catechin, chlorogenic acid, gallic acid, and ferulic acid were present only in the milk of goats grazed on pasture and were undetectable when goats were fed concentrates in confinement. Finally, concentrations of equol, formononetin (both isoflavones), and enterolactone (a lignan) are higher in milk from cattle grazed on pasture than in milk from feedlots (Hoikkala et al., 2007; Adler et al., 2015). Higher equol and/or enterolactone intakes are associated with a reduced risk of osteoporosis, prostate, and breast cancer, as well as lower circulating levels of low-density lipoprotein cholesterol and C-reactive protein (Jackson et al., 2011; Rodríguez-García et al., 2019).

Pasteurization is another factor impacting the polyphenol content of dairy. For example, Cuchillo-Hilario et al. (2009) found that the polyphenol content in pasture-raised goat cheese was 3-fold higher in raw milk cheese than when the milk was pasteurized prior to making cheese. While pasteurization is the norm in the US, consumption of raw dairy is more accepted in other parts of the world, including several European and African countries (Mattiello et al., 2018; Baars, 2019; Meunier-Goddik and Waite-Cusic, 2019). For example, in the Netherlands, Gouda farmhouse cheeses are required by law to conform to traditional production methods, which prohibit pasteurization (Fischer Boel, 2009). Similarly, French artisanal cheeses are often made from raw milk and are considered superior to pasteurized cheeses. Besides enhancing health, phytochemicals also enhance flavor (Clarke et al., 2020), which can become compromised with heat treatment. Proper animal husbandry and hygiene practices on farms would enable farmers to obtain raw milk of high microbiological quality (D'Amico and Donnelly, 2010; Janštová et al., 2011; Giacometti et al., 2013; Baars, 2019). Nevertheless,

TABLE 1 | Impact of livestock diets on phytochemicals in meat and dairy.

Study	Foodstuff; Treatments	Compounds measured in meat and dairy (potential health effects)	Differences in meat and milk as a result of diet
Terpenoids			
Larick et al. (1987)	Beef fat; Monoculture pasture—fescue vs. brome vs. orchard grass— vs. concentrates	Azulene (anti-inflammatory), 1,2-Phetene (anti-inflammatory, anti-oxidant), Phytane (anti-inflammatory), Phytol (anti-oxidant), and three more terpenes	↑5-fold in fescue pasture vs. concentrates; ↑2.5-fold in brome or orchard grass vs. concentrates
Martin et al. (2005)	Cow milk; Diversified mountain pasture vs. ryegrass monoculture vs. concentrates	α-Copaene (anti-oxidant), α-Thujene (anti-inflammatory), Camphene (anti-bacterial), o-Cymene (anti-inflammatory, anti-viral), and eight more terpenes	↑6- to 23-fold in diverse pasture vs. ryegrass vs. concentrates.
Priolo et al. (2003)	Lamb fat; Diversified pasture vs. concentrates	β-Caryophyllene (anti-inflammatory), α+ β-Cubebene (anti-viral, anti-carcinogenic), zonarene (anti-microbrial), and five more terpenes	↑6-fold in diverse pasture vs. concentrates
Agabriel et al. (2007)	Cow milk; Diversified mountain pasture vs. temporary pasture + hay vs. temporary pasture + concentrates	β-Elemene (anti-inflammatory, anti-tumor) β-Pinene (anti-inflammatory, anti-oxidant, anti-tumor) Sabinene (anti-inflammatory, anti-oxidant), and fourteen more terpenoids	↑2-fold in diverse pasture vs. temporary pasture + concentrates; ↑1.5-fold in temporary pasture + hay vs. temporary pasture + concentrates
Fedele et al. (2007)	Goat milk; Diversified shrubland vs. mixed hay (alfalfa, rye grass and orchard grass)	Δ-3 Carene, 4- and α + γ-Terpineol, β-Cedrene, β-Farnesene, Isolongifolene, and Longifolene (collectively—anti-inflammatory, anti-bacterial, anti-oxidant and/or anti-carcinogenic)	↑5-fold diverse pasture vs. mixed hay
Børge et al. (2016)	Cow cultured cream; Diversified mountain pasture vs. concentrates	Δ-3 Carene, α + β-Pinene, α-Thujene, β-Citronellene, Sabinene and four more terpenoids (collectively—anti-inflammatory, anti-bacterial, anti-oxidant and/or anti-carcinogenic)	↑5-fold in diverse pasture vs. concentrates
Coppa et al. (2019)	Cow milk; Pasture (mix of diverse and non-diverse) vs. concentrates	α-Thujene, α-Pinene, β-Citronellene, Caparratriene α+ β-Caryophyllene, and five more terpenoids (collectively—anti-inflammatory, anti-bacterial, anti-oxidant and/or anti-carcinogenic)	↑2-fold pasture (mix of diverse and non-diverse) vs. concentrates
Polyphenols			
Besle et al. (2004)	Cow milk; Diversified mountain pasture vs. ryegrass monoculture vs. concentrates	Total phenol content	↑3-fold in diverse pasture vs. concentrates; ↑2-fold in ryegrass pasture vs. concentrates
Cuchillo-Hilario et al. (2009)	Goat cheese; Diversified shrubland vs. concentrates + hay	Caffeic acid (anti-inflammatory, anti-oxidant, anti-carcinogenic), Quercetin (anti-inflammatory, anti-bacterial, anti-oxidant, anti-carcinogenic), and total polyphenol content	↑13-fold in diverse pasture vs. concentrates
Adler et al. (2015)	Cow milk; Diversified pasture vs. concentrates	Isoflavones: Daidzein, Formononetin, Genistein, Equol Lignans: Enterolactone, Secoisolariciresinol (collectively—anti-inflammatory, anti-carcinogenic, anti-osteoporotic, and/or neuroprotective)	↑3-fold in diverse pasture vs. concentrates
Chen et al. (2015)	Yak meat; Diverse pasture vs. concentrates	Total phenol content	↑1.5-fold in non-diverse pasture vs. concentrates
Cabiddu et al. (2019)	Goat milk; Diversified shrubland vs. concentrates	Total phenol content	↑1.2 (winter) to 5-fold (summer) in pasture vs. concentrates
Coppa et al. (2019)	Cow milk; Pasture (mix of diverse and non-diverse) vs. concentrates	3,4-Dimethylphenol, 2,6-Quinolinediol, and eight more phenolic compounds (collectively—anti-inflammatory, anti-oxidant, and/or anti-carcinogenic)	↔pasture vs. concentrates
Delgadillo-Puga et al. (2019)	Goat milk; Diversified shrubland vs. concentrates + 30% *Acacia farnesiana* (AF) vs. concentrates	Catechin, Chlorogenic acid, Gallic acid, and Ferulic acid (collectively—anti-inflammatory, anti-oxidant, anti-carcinogenic, and/or neuroprotective)	↑2-fold in pasture vs. concentrates + 30% AF; undetectable in concentrates

(Continued)

TABLE 1 | Continued

Study	Foodstuff; Treatments	Compounds measured in meat and dairy (potential health effects)	Differences in meat and milk as a result of diet
Carotenoids and Tocopherols			
Prache et al. (2003)	Lamb fat; Diversified pasture vs. concentrates + hay	Lutein (anti-inflammatory, anti-oxidant, macular degeneration protective)	↑2.8-fold diverse pasture vs. concentrates + hay
Gatellier et al. (2004)	Beef meat; Pasture (unspecified) vs. concentrates	Total tocopherol content	↑1- to 1.3-fold pasture vs. concentrates
Havemose et al. (2004)	Cow milk; Grass-based forage vs. corn-based forage	$\alpha+\delta+\gamma$-Tocopherol, β-Carotene, Lutein, and Zeaxanthin (collectively—anti-inflammatory, anti-oxidant, anti-carcinogenic, and/or neuroprotective)	↑3-fold grass-based vs. corn-based
Descalzo et al. (2005)	Beef; Pasture (unspecified) vs. concentrates	α-Tocopherol and β-Carotene	↑2- to 7.5-fold pasture vs. concentrates
Agabriel et al. (2007)	Cow milk; Diversified mountain pasture vs. temporary pasture + hay vs. concentrates	β-Carotene and Lutein	↔ pasture vs. temporary pasture + hay vs. concentrates
Butler et al. (2008)	Cow milk; Pasture (unspecified) vs. concentrates	α-Tocopherol, β-Carotene, Lutein, and Zeaxanthin	↑1.4- to 1.8-fold pasture vs. concentrates
Röhrle et al. (2011)	Beef fat; Non-diverse pasture vs. concentrates	Lutein and β-Carotene	↑3.3- to 6-fold pasture vs. concentrates
Coppa et al. (2019)	Cow milk; Grass-based forage vs. corn-based forage	β-Carotene	↑1.2-fold in grass-based

however small the risk of pathogenic presence may be—<0.3% in aforementioned studies, generally limited to single farms—zero-risk is not possible and consuming raw milk can have serious adverse health effects (O'Callaghan et al., 2019). Whether such small risks are acceptable in food systems and whether the consumption of raw dairy from pasture-based systems (milk from concentrated feeding operations is generally not sold raw) should be left to individual choice is beyond the discussion of our work (for a nuanced discussion of the topic, see Baars, 2019). Cooking meat also reduces polyphenol and terpenoid contents by 25–60% (King et al., 1993, 1995; Kozová et al., 2009; Dadáková et al., 2011), with higher heat preparations (e.g., grilling and roasting) resulting in higher reductions compared to lower heat preparations (e.g., stewing and "sous vide") (Kozová et al., 2009; Dadáková et al., 2011).

The contribution of phytochemicals from pasture-raised meat and milk to overall dietary intake should not be underestimated. While total phenolic levels (expressed as gallic acid equivalents) in fruits and vegetables (Deng et al., 2013) are generally 5 to 20-fold higher compared to pasture-raised meat and milk (López-Andrés et al., 2013; Chen et al., 2015; Cabiddu et al., 2019; Delgadillo-Puga et al., 2019), various individual phytochemicals are abundant in pasture-raised meat and milk. For example, the amount of chlorogenic acid (12.3 mg/100 g) in pasture-raised milk (Delgadillo-Puga et al., 2019) may be on par or higher than several vegetables and fruits such broccoli (5.5 mg/100 g), cowpea (0.7 mg/100 g), and tomatoes (8 mg/100 g) (Deng et al., 2013; Arnaud, 2016). Furthermore, López-Andrés et al. (2013) found total phenolic levels in pasture-fed lamb liver to be 6.6 mg GAE/g product, which is comparable to values found in several fruits and vegetables including eggplant (6.7 mg GAE/g) and turnip (6.0 GAE/g), squash (5.0 mg GAE/g) and snap bean (5.9 mg GAE/g). Muscle meat is about 4-fold lower in phenolics compared to liver yet can still contributes meaningful amounts of phytochemicals in the human diet (Chen et al., 2015). Most commonly known for their presence in green tea, the flavonoids catechin, gallic acid, and chlorogenic acid have been extensively studied for their anti-oxidant, anti-inflammatory, and anti-carcinogenic effects (Kroes et al., 1992; Khan and Mukhtar, 2007; Verma et al., 2013). Importantly, the quantity of gallic acid (1.3 mg/100 g) and catechin (4.3 mg catechin/100 g) in diverse pasture-raised milk (Delgadillo-Puga et al., 2019) is comparable to average quantities found in some green teas (1.2 mg gallic acid/100 g; 4.3 mg catechin/100 g, respectively) (Henning et al., 2003). Similarly, the presence of quercetin and caffeic acid, which are anti-oxidants best known for their presence in onions (McAnlis et al., 1999) and coffee (Nardini et al., 2002) have also been readily detected in cheese from goats grazing botanically diverse shrubs and grasses (De Feo et al., 2006; Cuchillo-Hilario et al., 2009), albeit at 30-fold lower concentrations than what is found in onions, but similar to levels in cabbage, celery, potatoes, and several other fruits and vegetables (USDA, 2016b). We stress that these examples should not be interpreted as a meat vs. plant foods discussion nor as "evidence" that animal foods negate a need for obtaining phytochemicals from plant foods. Plant and animal foods arguably improve human health in synergistic ways (Barabási et al., 2020; Van Vliet et al., 2020). Rather these examples serve to illustrate that pasture-raised animal foods can contribute substantially to phytonutrient intake in the human diet. Whether the potential beneficial effects of consuming phytochemically-rich meat and dairy are analogous to, but distinct from, benefits attained by eating phytochemically-rich herbs, fruits, and vegetables should be assessed in future studies. Importantly, by consuming phytochemically-rich meat and milk we ingest a broad spectrum of phytonutrients from classes of plants (e.g., a wide variety of *Monocotyledoneae* and *Dicotyledoneae)* otherwise not readily consumed by humans.

Carotenoids and Tocopherols

Carotenoids are a class tetraterpenoids found abundantly in plants and fruits. β-carotene is the main isomer found in plants, however other carotenoids such as α-carotene and the xanthophylls lutein and zeaxanthin are also widely found in plants (Khoo et al., 2011; Eisenhauer et al., 2017). Carotenoids are fat soluble with β-carotene being quantitatively most abundant and responsible for the yellow tint of the fat in grass-fed beef and cow's milk (goats and sheep do not accumulate β-carotene, hence their milk is whiter) (Nozière et al., 2006; Dunne et al., 2009). Carotenoids can serve as precursors of vitamin A in humans (Haskell, 2012), and their intake is associated with a wide variety of health benefits including improved cognitive function (Grodstein et al., 2007), reduced risk of metabolic diseases such as cancer (Nishino et al., 2009), cardiovascular disease (Voutilainen et al., 2006), and diabetes (Sluijs et al., 2015), protection from age-related macular degeneration (Seddon et al., 1994), as well as more broadly being defined as having anti-oxidative and anti-inflammatory effects (Ciccone et al., 2013).

Tocopherols are a class of phenolic compounds, with vitamin E activity, best known for their anti-oxidative effects. Tocopherols exist as four structural isomers (α, β, γ, and δ) with α-tocopherol being the predominant form in both livestock (Nozière et al., 2006) and humans (Kinsella, 2007). Similar to carotenoids, tocopherols protect against cardiovascular disease (Huang et al., 2019), certain cancers (Helzlsouer et al., 2000; Das Gupta and Suh, 2016), neurocognitive decline (Mangialasche et al., 2012), and age-related macular degeneration (Delcourt et al., 1999).

Similar to terpenoids and phenols, the nature of forage also impacts carotenoid and tocopherol levels in meat and milk. Highest concentrations are found in animal grazing diverse pastures, with lower concentrations found in meat and milk from animals grazing monoculture pastures or fed dried hay (due to ultraviolet-light degradation of carotenoids after harvesting), while animals fed concentrates have the lowest concentrations of carotenoids and tocopherols (Nozière et al., 2006; Dunne et al., 2009) (**Table 1**). Positive curvilinear relationships were found between carotenoid intake and milk content of cows (Calderón et al., 2007) and the fat content of sheep (Dian et al., 2007). Others also found that, as the ratio of forage-to-total-mixed-rations increases, α-tocopherol, β-carotene, lutein, and/or retinol concentrations increase in a curvilinear fashion in milk (Pizzoferrato et al., 2007; La Terra et al., 2010; Salado et al., 2018).

Similar to other phytochemicals, seasonality affects carotenoid and tocopherol content in meat and milk from pasture-based systems, with higher amounts observed during the spring compared to the summer, fall, and winter (Nozière et al., 2006; Marino et al., 2012; Jain et al., 2020). For example, Nozière et al. (2006) found that β-carotene is highest in pasture-fed cow's milk during the summer, declines 1.5-fold during the fall, is 2-fold lower during the winter, and climbs back up during the spring. Similarly, Jain et al. (2020) found ∼10% lower β-carotene and α-tocopherol in US grass-finished beef during the fall compared to the spring, in addition to slightly lower iron and zinc concentrations. Carotenoid content of meat experiences less seasonal variation compared to milk. That is because the transfer of phytochemicals from forage into milk occurs within days (Vialloninsta et al., 2000; Calderón et al., 2007), while the phytochemical accumulation in meat occurs slowly over the lifetime of the animal (Prache et al., 2003).

While tocopherols and carotenoids are several-fold more abundant in plant foods compared to animal foods, their presence is noteworthy as they can protect meat and milk from protein and lipid oxidation (Realini et al., 2004; Pizzoferrato et al., 2007; Gonzalez-Calvo et al., 2015), which may improve protein digestibility and amino acid availability (Lund et al., 2011), lower the formation of pro-inflammatory compounds such as aldehydes generated by cooking (Lynch et al., 2001), and increase shelf life (McDowell et al., 1996). Moreover, eating pasture-raised beef raised circulating α-tocopherol and β-carotene to 1.2 and 1.5 times higher concentrations compared to feedlot-finished beef (Tartaglione et al., 2017).

Anti-oxidant Capacity of Pasture-Raised Meat and Dairy

Oxidative stress—characterized by excessive concentrations of reactive oxygen species (ROS)—can damage proteins, DNA and RNA, and plays a major role in the development of chronic ailments such as cardiovascular (Dhalla et al., 2000) and neurodegenerative diseases (Kim et al., 2015), cancer (Reuter et al., 2010), arthritis (Quiñonez-Flores et al., 2016), diabetes (Giacco and Brownlee, 2010), and other chronic diseases (Pena-Oyarzun et al., 2018). Antioxidants act as ROS "scavengers" by preventing and repairing damage caused by ROS, thus strengthening the immune system and offering protection against developing chronic diseases (Lushchak, 2014).

The increased phytochemical richness of the diets of animals grazing botanically diverse pastures results in higher anti-oxidant capacity in meat and milk. Anti-oxidant capacity is reduced when animals forage on monocultures of grass and the lowest anti-oxidant capacity occurs in meat and milk produced from animals fed concentrates in confinement (Descalzo et al., 2005; Cuchillo-Hilario et al., 2009; Kuhnen et al., 2014; Delgadillo-Puga et al., 2019) (**Table 2**). For example, Delgadillo-Puga et al. (2019) found that antioxidant capacity of pasture-raised goat's milk, assessed by its ferric ion antioxidant power (FRAP) (Huang et al., 2005), was 1.5- to 2.5-fold higher than milk from goats fed concentrates. Importantly, they found that anti-oxidant capacity of the milk was strongly correlated with the presence of phenols.

Descalzo et al. (2007) found that grass-fed beef also had a 1.5-fold higher FRAP capacity than beef from grain-fed animals. Additionally, compared to grain-fed beef, grass-fed beef had a higher glutathione content and redox potential (glutathione is one of the most potent intracellular antioxidants), and superoxide dismutase activity (an enzyme providing cellular defense against ROS) (**Table 2**). No differences were observed for other measures of anti-oxidant status such as Trolox equivalent antioxidant capacity (TEAC), catalase (CAT), and glutathione peroxidase (GPx). In contrast, Gatellier et al. (2004) found

TABLE 2 | Impact of livestock diet selection on anti-oxidant activity in meat and dairy.

Study	Foodstuff; treatments	Anti-oxidant activity of pasture vs. concentrate-finished meat and dairy (↑,↔, or↓); assay type
Anti-oxidant status		
Gatellier et al. (2004)	Beef meat; Pasture (unspecified) vs. Concentrate	↔ABTS, 1.1-fold ↓OH-Benzoate, 4-fold ↑SOD, ↔CAT, and 2.5-fold ↓GPx
Descalzo et al. (2005)	Beef meat; Pasture (unspecified) vs. concentrate	↔ABTS, 1.5-fold ↑FRAP, 1.8-fold ↑Glutathione, 1.1-fold ↑Glutathione redox potential, 1.4-fold ↑SOD, ↔CAT, and ↔GPx
López-Andrés et al. (2013)	Lamb liver; Monoculture pasture (ryegrass) vs. concentrate	1.3-fold ↑FRAP and 1.2-fold ↑Folin–Ciocalteu
Cuchillo-Hilario et al. (2009)	Goat cheese; Diversified shrubland vs. concentrates + hay	2-fold ↑ABTS and 1.6-fold ↑DPPH
Chen et al. (2015)	Yak meat; Diversified pasture vs. concentrate	1.4-fold ↑ABTS and 1.1-fold ↑FRAP
Delgadillo-Puga et al. (2019)	Goat milk; Diversified shrubland vs. concentrate	1.5-fold ↑DPPH, ↔FRAP, and 2.5-fold ↑ORAC
Luo et al. (2019)	Lamb fat; Diversified pasture vs. concentrate	1.5-fold ↑ABTS, 1.1-fold ↑CUPRAC, ↔ SOD, 1.6-fold ↑CAT, and 1.7-fold ↑GPX

ABTS, 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid); CAT, catalase; CUPRAC, cupric ion reducing antioxidant capacity; DPPH, 2,2-diphenyl-1-picrylhydrazyl; FRAP, ferric ion antioxidant power; GPx, glutathione peroxidase; ORAC; oxygen radical absorbance capacity.

higher CAT and GPx activity for animals fed concentrates indoors compared to pasture-grazed animals, whereas the reverse was found for SOD activity. While the reasons for these divergent findings are unclear, a potential explanation is that the concentrate-fed animals were finished on private farms for only 3 months during the winter, which may not represent "typical" feedlot environments where animals are finished on concentrates for an average of 5 months (Drouillard, 2018). As the authors point out, the findings of their study may indicate a "production system effect" rather than a diet effect. Contrary to the feedlot-finished animals, pasture-finished animals can more freely engage in natural behaviors, which could further positively impact their anti-oxidant status (Gatellier et al., 2004). Finally, López-Andrés et al. (2013) found higher anti-oxidant activity (assessed by FRAP and Folin–Ciocalteu assays) in the liver of lambs raised on pasture compared to lambs fed concentrates in confinement.

Taken together, these data suggest that pasture-raising and finishing is beneficial for both the health of the animal and its meat and milk products. It is perhaps no surprise that the two are connected: a healthier animal provides healthier meat and milk. While the phytochemical richness and anti-oxidant capacity is enhanced in grass-fed meat and dairy, especially when raised on nutrient-rich species-diverse pastures, compared to animals that fed grain-based concentrates in confinement (e.g., feedlots), the question remains: Does the increased phytochemical richness of grass-fed meat and dairy have an appreciable effect on improving human health?

THE EFFECTS OF ANIMAL PRODUCTION SYSTEMS ON HUMAN METABOLIC HEALTH

The metabolic effects of consuming grass-fed meat and dairy vs. feedlot-finished counterparts have predominantly been studied for their ability to modulate inflammation and lipoprotein profiles (e.g., cholesterol and triglycerides). Low-grade systemic inflammation—characterized by elevated levels of the cytokines interleukin-6 (IL-6), tumor necrosis factor-alpha (TNF-α), and/or C-reactive protein (CRP)—participates in the development of metabolic diseases such as heart disease, cancer, type II diabetes, and arthritis (Libby, 2007). Importantly, cytokines are modulated in response to single meals (Holmer-Jensen et al., 2011), with compounding effects on the progression of metabolic disease when single meals that raise inflammation become dietary habits (Esposito and Giugliano, 2006). Modulating the inflammatory milieu by dietary choices, therefore, represents an important strategy to prevent or treat metabolic disease.

In a randomized cross-over design, Arya et al. (2010) found that eating kangaroo meat, obtained from animals foraging on native pastures, attenuated the postprandial rise in IL-6, TNF-α, and CRP compared to feedlot-finished (grain-fed) beef. A limitation of the study is that, despite all of the fat being cut off of both the beef and kangaroo steak, the kangaroo was presumably still leaner than the beef, which could have confounded the results. Another study found that daily consumption of pecorino cheese—made from sheep who foraged on diverse pastures in Tuscany, Italy—for 10 weeks reduced circulating levels of pro-inflammatory cytokines and improved erythrocyte deformability, which is indicative of improved red blood cell function (Sofi et al., 2010). Werner et al. (2013) showed similar decreases in CRP over 12-weeks with daily consumption of 39 g of butter from either mountain-raised or feedlot-fed cattle, despite a lower SFA content and improved ω-3-to-ω-6 ratio in pasture-raised butter. Total daily saturated and polyunsaturated fat intake was similar between groups, which could have washed-out any effects of the butter *per se*. No effect of either intervention was observed for lipid profiles, insulin sensitivity, or glucose tolerance.

Gilmore et al. (2011) found that consumption of 113g of beef, 5 times per week for 5-weeks, from cattle raised on non-diverse pasture (coastal Bermuda grass) or grain-finished in feedlots does not differentially impact inflammatory profiles (Gilmore et al., 2011). As highlighted in **Tables 1** and **2**, the phytochemical richness and anti-oxidant capacity is reduced in meat from animals raised on monoculture pastures compared to meat from animals with access to more forage diversity, and that could be a reason for the lack of changes in inflammatory biomarkers in this work. However, future clinical trials comparing inflammatory responses to botanically diverse diets vs. monoculture grass-fed diets vs. grain-fed meat (and dairy) are needed to test this hypothesis.

In the work of Gilmore et al. (2011), eating grain-fed beef patties also resulted in higher circulating levels of total high-density lipoprotein cholesterol (HDL-C) and triglycerides (Adams et al., 2010; Gilmore et al., 2011), but that was not observed when the group ate pasture-raised beef patties. When considering HDL-C differences by particle size, no differences were observed in large and medium HDL particle size between interventions. Levels of large HDL particles show the strongest inverse relationship with cardiovascular risk compared to other HDL particle sizes in population-based studies (Mora et al., 2007; Van Der Steeg et al., 2008). In contrast, Brown et al. (2011) found that consuming dairy and meat from pasture-fed cattle for 8 weeks did not alter lipoproteins profiles, body composition, or glucose tolerance compared to a diet comprised of products from grain-fed cattle. Fatty acid profiles were similar for SFA, MUFA, and PUFA, only CLA was higher in the group that consumed pasture-fed meat and milk. Unfortunately, no information was provided on the diet fed to pasture-raised and grain-fed cattle. Taken together, these data suggest the lipid content of animal products may affect lipoprotein profiles of consumers, and that pasture-raised meat and milk may have greater anti-inflammatory properties compared to feedlot-finished animals. However, evidence is too sparse to make definitive claims and further clinical nutrition trials are needed.

SUITABILITY AND SCALABILITY OF PASTURE-BASED LIVESTOCK SYSTEMS

Grass-fed beef represents 4% of the US beef market (Cheung and McMahon, 2017) and organic milk represent 5.5% of the US dairy market (Gerdes, 2019). Organic milk that is truly from pasture-raised cattle may represent only 0.5%, though that market is growing rapidly and achieved a 58% increase in sales in 2018 (Gerdes, 2019). While concentrated animal feeding operations (CAFOs) are the predominant model in the US, in countries such as New Zealand, Australia as well as some European, South-American, and African nations the finishing model may be increasingly pasture-based. Especially in the US and Western countries the issue is complicated by confusion over the many labels—such as "organic," "grass-fed," "pasture-raised," and "free-range"—that consumers generally associate with healthier products. For example, organic does not necessarily mean animals were raised and finished on pasture. According to the USDA, the requirement is for cattle to have free access to certified-organic pasture for the entire grazing season (at least 120 days), while only 30% of the cattle's diet needs to come from pasture (USDA, 2016a). In the recent past, US farmers could make a good living by switching to organic production, but organic dairying is becoming a victim of its own success. A handful of large scale "organic" dairies—which now feed thousands of cows a diet of organic grain and stored forages with limited access to pasture—produce more milk than all organic, grass-fed dairy farms in Wisconsin combined (Whoriskey, 2017). To further complicate the matter, grass-fed also does not necessarily mean animals were raised on pasture without confinement (Provenza et al., 2019). Even the term "grass-fed" can mean animals were fed grass pellets in a feedlot-type production model or were grazing monoculture grasses. As we have described, this does not result in similar phytochemical richness and favorable fatty acid profiles compared to animals raised on pasture with access to a wide variety of different grasses, forbs, and shrubs. The uncertainty about product quality may be the result of a change in the USDA Agricultural Marketing Service (AMS) regulation of standards for "grass-fed." While the claim "grass-fed" can still be made through the USDA, AMS discontinued the verification of the applicant's programs to the Standard in 2016. To truly know whether animals were raised on pasture, consumers would have to rely on third-party verification (e.g., "100% Pasture-Raised," "Global Animal Partnership 5-Step® Animal Welfare Rating," "Regenerative Organic Certified™″ etc.), establish contact with local farmers, and/or use Internet resources to gain insight into production practices of farmers.

With increased conversion to pasture-based beef production systems in the US, some suggest that domestic beef consumption will have to be reduced by about 40% due to lack of land (Hayek and Garrett, 2018). This estimate includes feeding roughage on pasture and is based on the current status quo of continuous grazing practices. To help meet needs, most people in high-income countries, such as the US and Europe, can reduce red meat consumption with no harm to their health, and likely even improve their health when diet quality would increase as a result (Fogelholm et al., 2015; Grosso et al., 2017; Guasch-Ferré et al., 2019). However, there are several opportunities by which improved management practices can increase the carrying capacity of livestock in pasture-based models, while enhancing ecosystem function. For example, grazing management practices that use ecological principles can increase the carrying capacity of livestock by 50–70% compared to continuous (largely unmanaged) grazing (Jacobo et al., 2006; Jakoby et al., 2015; Wang et al., 2016; Teague and Kreuter, 2020). This is a key point in discussions on whether pasture-based systems can support demand and productivity (Gerrish, 2004). Managed grazing positively influences plant-soil interactions, including plant root exudation and mycorrhiza (Gianinazzi et al., 2010), by recycling nutrients in feces and urine back into the soil through the actions of microorganism and small soil animals (e.g., earthworms and dung beetles) (Holter, 1983; Nichols et al., 2008; Menta and Remelli, 2020), which improves soil health and ecosystem function. Moreover, nutrient-rich soils and plant biomass have potential to improve the health of animals and humans by increasing the phytonutrient density (e.g., terpenoids, phenols, and other anti-oxidants) of pasture-raised meat and milk. In support of the soil-plant-animal-human health connection is that grazing nutrient-rich soils can positively impact the mineral content of grass-fed beef (Leheska et al., 2008). Additional long-term ecosystem benefits from agroecological grazing systems include increased plant and animal biodiversity, carbon sequestration, wildlife habitat, water infiltration and retention, and last but not least, improved resiliency and profitability for farmers through reduction of input cost (Gerrish, 2004; Meuret and Provenza, 2015; Teague and Kreuter, 2020). For a further discussion on soil health and ecosystem function in the context of agroecological grazing systems we refer the reader to the recent work of Teague and Kreuter (2020).

There is also potential for increased carrying capacity from multi-species grazing with little dietary overlap. For instance, integrating cattle with sheep, goats, and pigs and/or potentially other feed-conversion-efficient herbivores such as ducks, geese, and rabbits can improve animal productivity compared to grazing single species (Dumont et al., 2020; Martin et al., 2020) This synergy is achieved because different species exploit different ecological niches and one species can increase resource availability for another species (Walker, 1994; Anderson et al., 2012; Dumont et al., 2020). This would mean that we would have to diversify our meat and milk intake to include products from other livestock such as goats, sheep, bison, duck, geese, and rabbits to name a few. It is noteworthy that consumption of products from many of these livestock is already common practice on other parts of the world or are increasing rapidly in the US (e.g., bison consumption).

Greater diversification of livestock can allow for more efficient use of the resources provided by a particular ecosystem. For example, goats and sheep readily eat species of forbs, shrubs and trees that large herbivores like cattle and bison often avoid, while larger herbivores can better utilize lower quality forage compared to small herbivores such as sheep and goats (Steuter and Hidinger, 1999; Fraser et al., 2014; Cuchillo-Hilario et al., 2018; Martin et al., 2020). These examples illustrate that selection of animals that most effectively use, and more importantly, conserve the natural resource base in a given geographical location should be a key consideration to improve the efficiency and scalability of pasture-based livestock systems. For example, in the US, 53% of all red meat consumed is from beef, 46% is from pork, while <1% comes from other herbivores (STATISTA, 2019). Limiting consumption to only two to three species conflicts with herbivore diversity found in natural ecosystems, and arguably the level of diversity that is desired in agroecologically appropriate livestock systems.

Differences in phytochemicals and fatty acids between animal species further illustrates the importance of livestock diversification—different species provide different nutrients in the human diet. For example, β-carotene and lutein is lower in the meat and milk of goats and sheep compared to bovines (Yang et al., 1992; Lucas et al., 2008). On the other hand, retinol (vitamin A) concentrations are 2-fold higher in milk and meat of ovines compared to bovines (Martin et al., 2004; Darwish et al., 2016), owing to a higher efficiency of converting carotenoids into retinol in ovines (Yang and Tume, 1993). The ω-3 fatty acid content of milk and meat from goats is also 1- to 2-fold higher compared to cow's milk and meat, while cow's milk contains 1.5- to 2-fold higher concentrations of CLA compared to goat's milk (Yang et al., 1992; Lucas et al., 2008). Finally, lamb meat contains 1.5- to 2-fold higher concentrations of CLA compared to beef (Schmid et al., 2006).

Strategic supplementation of livestock on pasture with industrial by-products, inedible to humans (Sunvold et al., 1991; Macdonald et al., 2007), also has potential to increase the carrying capacity of pasture-based grazing systems and mitigate potential welfare issues associated with feedlots, such as reduced ability to express natural behavior and self-selection of diets (Atwood et al., 2001; Villalba and Manteca, 2019). For example, feeding limited amounts of phytochemically-rich fruit and vegetable by-products such as leaves, pomace, peels, rinds, pulp, seeds, and stems (Sruamsiri, 2007; Wadhwa and Bakshi, 2013; Salami et al., 2019) to livestock on pasture can potentially mitigate some nutritional deficits, decrease environmental impacts, and reduce the of risk of overgrazing and land unavailability, while enhancing the phytochemical richness of meat and milk (Provenza et al., 2003, 2019; Salami et al., 2019).

To improve the health and fertility of soils, many farmers in North and South America, Europe, and elsewhere are adding cover crops into rotations with cash crops such as wheat, corn, and soybeans on millions of hectares of land. Cover crops can be grasses or broadleaf plants—ideally mixtures of both—and are often rich in phytochemicals. They can be grown in the fall after cash crops are harvested or grown through the entire growing season. However, there are seed and seeding costs for growing cover crops, and a good way for farmers to reclaim these expenses is to graze them with livestock (Bergtold et al., 2019). Grazing not only helps justify the costs of growing cover crops, but cover crops increase carrying capacity by providing feedstuffs to livestock and reducing negative environmental externalities such as soil erosion and chemical runoff associated with both crop and livestock farming (Fisher et al., 2012; Bergtold et al., 2019). These ecosystem services are achieved by nutrient recycling, reduced need for pesticide application, and by strengthening soil-plant-herbivory interactions to achieve synergy between agricultural production and environmental quality (Lemaire et al., 2014). Therefore, cover crop grazing provides further potential to increase land and forage available to pasture-based livestock production systems, while providing important agroecological benefits.

Strategies that integrate multi-species grazing, mixed crop-livestock systems, and/or phytochemically rich by-product feeding should not be viewed as "silver bullet" approaches to climate change or to meet an ever-growing demand for red meat. However, practices that promote good land stewardship and effective use of resources should be incentivized to sustain and improve the natural resource base upon which agriculture depends—in turn, benefiting the presence of health-promoting compounds in meat and milk from productive soils and vegetation.

We do not expect one paradigm (pasture-based grazing systems) to simply replace the other (feedlot-fed systems). That is not how shifts occurred historically. However, as paradigms gain momentum based on mounting evidence in their favor (e.g., the potential of managed grazing to increase the health of soils, plants, animals, and humans), new combinations of practices emerge. Eventually those practices come to better suit the ideas and the interests of various stakeholders (e.g., consumers, farmers, institutions, and industry). Given the environmental and human health concerns regarding the high-input feedlot model, the livestock industry will arguably have to shift toward an increasingly regenerative hybrid in the future. Even within pasture-based systems, there will be a need for a paradigm shift from conventional (e.g., unmanaged systems that risk overgrazing and land degradation) to agroecological practices that mimic processes of natural ecosystems (e.g., adaptive grazing, integrated crop-livestock systems, multi-species grazing, silvopasture systems etc.). If changes are not taken on an industry wide-scale, the livestock industry may be at risk from increasing societal and institutional pressures to adopt policies that will eventually force change (e.g., through loss of market shares and taxation). Concerns about climate change and associations of red meat and dairy with metabolic disease risk have led to rapid expansion of substitutes, which are touted as better than traditional meat and dairy for environmental and human health (Clay et al., 2020; Van Vliet et al., 2020). Moreover, food policy now questions whether red meat should even be consumed as part of environmentally friendly and healthy diets by future generations (Lucas and Horton, 2019; Willett et al., 2019; WBCSD, 2020), despite having nourished *Homo Sapiens* and its ancestors for the last 1.5 to 3 million years (Gupta, 2016; Andrews and Johnson, 2020).

CONCLUSION

Plant diversity—and associated phytochemical richness—links animal, human, and environmental health (Provenza et al., 2019). In addition to reducing per capita consumption of meat in industrialized countries (Godfray et al., 2018), human and environmental health can be enhanced through livestock management practices that promote good land stewardship, limit environmental impacts (Wepking et al., 2019; Andrews and Johnson, 2020; Richter et al., 2020; Rosenzweig et al., 2020), and enhance the healthfulness of meat and dairy products (Provenza et al., 2019). While public health recommendations are for reducing red meat consumption to reduce risk of metabolic disease, no consideration is given to animal production practices in these dietary recommendations. That is likely because the literature on animal production systems and human health is limited.

Forage selection by livestock impacts the phytochemical richness of meat and dairy products, with greater botanical diversity resulting in both a wider variety and higher concentrations of health-promoting phytonutrients in meat and milk (**Figure 1**). Conversely, these phytonutrients are typically undetectable or present in lower concentrations in meat and milk from animals fed grain-based concentrates in confinement. The presence of phytonutrients in animal foods currently remains underappreciated, and is virtually unheard-of in discussions of nutritional differences between pasture-raised (grass-fed) and feedlot-finished (grain-fed) meat and milk, which have focused myopically on omega-3 fatty acids and CLA (Provenza et al., 2019). For this reason, is it often stated that little to no differences exist between grass-fed or grain-fed meat and milk; however, the reductionist focus on fatty acids vastly underestimates the complexity of natural food matrices. It is in the expanded pool of phytonutrients (e.g., terpenoids, phenolics, carotenoids, and tocopherols) where substantial differences between grass-fed and grain-fed meat and milk are observed.

The expanded pool of phytonutrients must be considered in attempts to understand the effects of meat and dairy consumption on human health, such as the dampening of inflammation and oxidative stress linked with cancer, heart disease, and metabolic syndrome—diseases that have been associated with red meat and dairy consumption (Ganmaa et al., 2002; Micha et al., 2012; Zheng et al., 2019; Fraser et al., 2020; Zhong et al., 2020). Though research is sparse, several studies show a potential for anti-inflammatory effects and improved lipoprotein profiles when people consume pasture-raised meat and dairy. How increasing the phytonutrient density of animal foods will modify potential relationships between consumption and metabolic health of consumers needs to be further addressed in clinical studies.

Future research should systematically assess the linkages between phytochemical richness of herbivore diets, the nutrient density of animal products, and their subsequent effects on human metabolic health. This is important as a rich body of agricultural literature exists on the presence of health-promoting phytonutrients—terpenoids, phenols, carotenoids, and tocopherols—in grass-fed meat and milk that have rarely been evaluated in clinical trials for their potential to modulate human health responses to meat and milk consumption. Given the concerns about red meat consumption on human health and the growing interest among producers and consumers in grass-fed meat and dairy products, clinical nutrition studies evaluating cardiometabolic risk biomarkers in response to phytochemically-rich meat and dairy represents a logical next step in the field. Finally, future studies should elucidate critical—and as yet unstudied—linkages between soil health, plant diversity, and the health of livestock and humans. Addressing this research gap will require greater collaborative efforts from the fields of agriculture and medicine.

AUTHOR CONTRIBUTIONS

SV wrote the first draft of the manuscript. FP and SK provided many suggestions to improve the manuscript. All authors approved the final version of the manuscript.

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The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Domestic Livestock and Rewilding: Are They Mutually Exclusive?

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Human influence extends across the globe, from the tallest mountains to the deep bottom of the oceans. There is a growing call for nature to be protected from the negative impacts of human activity (particularly intensive agriculture); so-called "land sparing". A relatively new approach is "rewilding", defined as the restoration of self-sustaining and complex ecosystems, with interlinked ecological processes that promote and support one another while minimising or gradually reducing human intervention. The key theoretical basis of rewilding is to return ecosystems to a "natural" or "self-willed" state with trophic complexity, dispersal (and connectivity) and stochastic disturbance in place. However, this is constrained by context-specific factors whereby it may not be possible to restore the native species that formed part of the trophic structure of the ecosystem if they are extinct (e.g., mammoths, *Mammuthus* spp., aurochs, *Bos primigenius*); and, populations/communities of native herbivores/predators may not be able to survive or be acceptable to the public in small scale rewilding projects close to areas of high human density. Therefore, the restoration of natural trophic complexity and disturbance regimes within rewilding projects requires careful consideration if the broader conservation needs of society are to be met. In some circumstances, managers will require a more flexible deliberate approach to intervening in rewilding projects using the range of tools in their toolbox (e.g., controlled burning regimes; using domestic livestock to replicate the impacts of extinct herbivore species), even if this is only in the early stages of the rewilding process. If this approach is adopted, then larger areas can be given over to conservation, because of the potential broader benefits to society from these spaces and the engagement of farmers in practises that are closer to their traditions. We provide examples, primarily European, where domestic and semi-domestic livestock are used by managers as part of their rewilding toolbox. Here managers have looked at the broader phenotype of livestock species as to their suitability in different rewilding systems. We assess whether there are ways of using livestock in these systems for conservation, economic (e.g., branded or certified livestock products) and cultural gains.

Keywords: rewilding, livestock, Oostvaardersplassen nature reserve, conservation, safe operating space, first nations, ecosystems services

INTRODUCTION

Across the globe, there is a growing recognition of the importance of wild landscapes for human wellbeing and the preservation of biodiversity and scenic values. In the USA this is driven by the wilderness agenda, whereas in parts of Europe it is because of the abandonment of pastoral systems of production as people move to the cities. Perhaps counterintuitively there is significant politics surrounding these areas where population densities are very low (Monbiot, 2014). This is because without deliberate intervention, landscapes may change in ways that are not desired by the public (e.g., forest encroachment in the French Alps; MacDonald et al., 2000). To avoid this scenario, managers need to decide when and how to intervene—even if the previous system of land management is no longer feasible. It is these contexts in which the connection between society and nature will play out. Thinking, imagining and acting will be key, because just doing nothing and letting nature take its course could lead to perverse outcomes (e.g., wildfires, loss of rare ecological assemblages such as grasslands), that will change the political agenda and humanity's relationships with nature. Now is the time to move beyond landscapes as simply a by-product of our production systems to deliberative *thoughtscapes,* and ultimately *actionscapes* before it is too late (portended by the recent fires in Australia and the western USA).

Nowhere on Earth is truly wild, human influence extends across the globe from the tallest mountains to the bottom of the deepest oceans (Goudie, 2018). These influences can be direct (e.g., land-use change, fishery harvest) and indirect (e.g., greenhouse gas emissions, pollution into rivers and coasts) (Rockström et al., 2009). Since the Pleistocene, humans have had negative impacts on ecosystems (over 75% of the land surface being significantly altered by human activity and over 85% of wetland area lost), and on species (with ∼25% of species threatened with extinction) (IPBES, 2019). This is likely to get worse as human populations grow and the global consumption of goods increases, both in developed countries and in emerging economies. It is commonly perceived that there is a conflict between human needs, for example, food production to meet the increasing demands (which is expected to grow by over 70% in the next 30 years) of the human population that is growing in size and wealth, and nature conservation (Gordon et al., 2017). The argument is that nature must be protected from the negative impacts of intensive agricultural production; so-called "land sparing" (Fischer et al., 2008). The extreme example of this is "rewilding", defined as "the reorganisation of biota and ecosystem processes to set an identified social–ecological system on a preferred trajectory, leading to the self-sustaining provision of ecosystem services with minimal ongoing management" (Pettorelli et al., 2018). It should be noted that rewilding is, in effect, a sub-set of restoration of ecosystems based upon the idea that restoration is "the process of assisting the recovery of an ecosystem that has been damaged, degraded or destroyed", Society for Ecological Restoration International Science and Policy Working Group (2004). Following its introduction in the academic literature in the late 1990s, rewilding has gained significant momentum in recent years (average just over 3 publications per year in the 2000s to around 80 publications per year in 2018 and 2019; **Figure 1**; see also Svenning et al., 2016; Pettorelli et al., 2019). This reflects the growing concern about the impacts of humans on natural systems, particularly as related to their wilderness [as in the case of the US Wilderness Act (1964)], the conservation of biodiversity (Johns, 2019), and a concern that current approaches are not effective (Butchart et al., 2010; Tittensor et al., 2014; WWF, 2016; IPBES, 2019). This in turn often sees humans as separated from wilderness areas e.g., "an area of land untrammelled by man, where man is a visitor who does not remain" [Section 2(c) of the US Wilderness Act (1964)] or "A wilderness is an area governed by natural processes. .... without intrusive or extractive human activity" (Wild Europe Initiative, 2013).

Though there have been attempts by academic ecologists to define and steer rewilding as a concept (e.g., Pettorelli et al., 2019), its undoubted intuitive resonance with non-academics (Monbiot, 2014) means it is destined to be a panchestron (all things to all people). We expect its definition will continue to develop as an emergent property as different kinds of rewilding emerge (rewilding is, after all, about "self-willed" processes where rewilding is possible). We believe this flourishing diversity of definitions should be embraced because we see several major concerns with adopting an overly purist approach to rewilding, i.e.:

(1) there are few places in the world where "pure" rewilding is possible – most have some form of social or ecological constraint (Fuller et al., 2017; Ward, 2019);
(2) humans have been part of wild landscapes for millennia, and the separation of humans from ecological systems runs counter to the broader view of socio-ecological systems in many other areas of academic and practical endeavour (Ostrom, 2009; Perino et al., 2019);
(3) the extinction of many keystone species (ecosystem engineers) from continents across the globe means that the restoration of functionally important native species is not possible in many cases (Sandom et al., 2014a,b; Richmond et al., 2016); and,
(4) it is not necessary to "de-domesticate" congeners of extinct wild species to achieve the outcomes we want where we have hardy domestic breeds that most likely have ecologically equivalent, or near identical, impacts if kept in wild/semi-wild conditions. These breeds can fulfil ecological functions that reinstate processes representative of wilded systems.

For these reasons we see the potential benefits of including species of domestic (e.g., cattle, goats, sheep, horses/ponies, pigs) and semi-domestic (e.g., reindeer) livestock in the toolkit of managers responsible for rewilding. Unlike many proposed functional "niche substitutes" where rewilding involves evolutionarily distinct species to replace lost processes [(e.g., African lions (*Panthera leo*) to replace predation by sabre-toothed cat (*Smilodon* spp.) in North America; Donlan, 2005; Lundgren et al., 2020)], many domesticated species are the same species, or closely related, to the species that have been lost from the landscape (Lundgren et al., 2020). Logically,

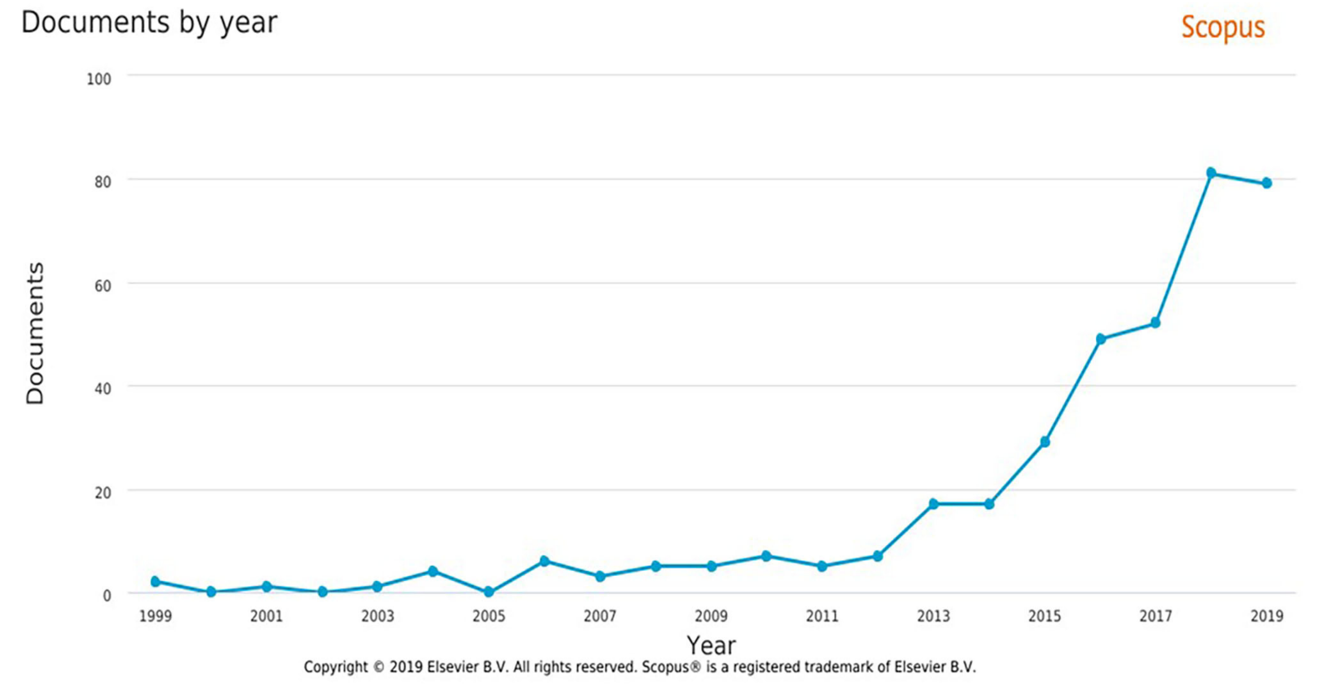

FIGURE 1 | Number of articles listed in Scopus that mention "rewilding" or "re-wilding." The search led to 370 papers.

this means that the domestics' ecological function will be very similar to their wild ancestors/relatives, the key differences likely related to impacts of husbandry on social structure, mate choice by humans (selection), constraints on spatial movements, aggression, and body size (Clutton-Brock, 1989). However, it is not clear that these would significantly influence the ecological function if domestic animals were maintained "as-wild". Indeed, the Chillingham cattle in Northumberland (United Kingdom), that are thought to be derived from domesticated animals, have been maintained as-wild for at least 700 years, and live "probably close to the natural state" (p. 215) (Hall, 1989). The cattle display many wild behaviours, and rarely exhibit some behaviours associated with husbanded cattle (Hall, 1989). This raises questions about whether de-domestication (the process of turning domestic breeds into wild, self-sustaining animals; Gamborg et al., 2010) is systematically necessary to achieve rewilding goals if existing hardy livestock breeds are permitted to live as wild animals. If not, the use of hardy breeds which are less aggressive [noting there concerns that auroch (*Bos primigenius*) may be "too dangerous"; Stokstad, 2015] and have production value, might encourage livestock keepers to develop systems that deliver on rewilding principles. This would of course require a re-evaluation of the characteristics of rewilding and/or rewilded landscapes, changes in policy/regulation, financial mechanisms (e.g., subsidies), and changes in attitudes, particularly amongst some environmentalists and conservationists.

It is worth noting that, as compared to rewilding in the academic literature (with over 370 articles and reviews) the inclusion of AND "livestock" in our search turned up only 21 articles and reviews since 1980, with seven appearing in 2019 (**Supplementary Material 1**). These include publications on the relationship between livestock and predators/scavengers (Arrondo et al., 2019), and advocacy for multifunctional landscapes based upon extensive livestock production for economic, conservation and carbon storage outcomes (Hall, 2018). However, to date there has been no clear articulation of the potential for including livestock within the rewilding agenda. In fact, it is generally declared that livestock are not part of the equation for rewilding unless, of course they have been used to 'reconstruct' wild progenitors of domestic species (e.g., Heck cattle; Heck, 1951; Stokstad, 2015). Obviously, the role that livestock might play in rewilding will be context-specific, but it is by no means unique to only certain specificities (e.g., in the heavily transformed landscapes of Europe). For this reason, we will set out the stall for:

(1) the fact that, no matter how large, rewilded landscapes cannot be isolated from human activity, and therefore, management will be required even if it is to achieve 'an area governed by natural processes";
(2) that livestock should be included in the toolbox of such management actions;
(3) that livestock can provide an economic return for such management actions; and,
(4) in the long-term rewilding needs to be seen within a broader socio-ecological system, where external influences will shape the future of wild landscapes.

THE BROADER THEORY OF REWILDING AND POTENTIAL ROLE FOR LIVESTOCK

Since the concept of rewilding was first published in the late 90s (Soule and Noss, 1998), with a focus on the "three Cs" (i.e., carnivores, corridors, and core areas), several variants of its definition have been proposed (Jørgensen, 2015), ranging from passive approaches on abandoned land (Navarro and Pereira, 2012) to the reintroduction of functional equivalents of the extinct megafauna of the Pleistocene (Donlan et al., 2006). While seemingly different, these approaches converge on the concept at the core of rewilding, which is the restoration of self- sustaining and complex ecosystems, with interlinked ecological processes that promote and support one another while minimising or gradually reducing human intervention. Recently, the ecological theory supporting rewilding allowed the formulation of a framework focusing on three ecological processes that interact with one another, and that should be restored to return an ecosystem to a wilder and self-sustainable state (Perino et al., 2019): (1) stochastic disturbances; (2) dispersal; and (3) trophic complexity. In the following sub-sections, we discuss the three ecological processes core to rewilding, the potential limits to their restoration, and the role that domestic species can play in the process.

Stochastic Disturbance Regimes

Disturbances that are natural in frequency and intensity promote spatial and temporal heterogeneity of habitats and the complexity of their structure (Turner, 1998; Kulakowski et al., 2017; Perino et al., 2019). Typical disturbances are, for instance, those created by large herbivores through their foraging, defecation and trampling (Navarro et al., 2015; Ripple et al., 2015). Fire regimes are also critical disturbances for the creation and maintenance of ecosystems (Bowman et al., 2009), and these are directly influenced by the grazing and browsing pressure (van Langevelde et al., 2019).

One of the most pervasive effect of human activities in a landscape, in addition to land- use change, is the alteration of the natural disturbance regimes: natural fires are suppressed (Archibald et al., 2013), and the stochastic disturbance by wild herbivores is replaced by long term deterministic disturbance by livestock and agronomic fertiliser application (Navarro et al., 2015; Perino et al., 2019). These anthropogenic landscapes have characteristic plant and animal assemblages that reflect the fact that herbivory has created and maintained assemblages that rely directly or indirectly on disturbance, historically by now extinct large herbivore species but now mainly by domestic livestock (Gordon et al., 2017; Bond, 2019). These modified ecosystems, and the economic, social, and cultural activities that depend upon them, are at risk once those livelihoods are abandoned (Cava et al., 2018; Van Meerbeek et al., 2019). Depending on the land-use legacy and the naturalness of the broader landscape, the abandoned land is vulnerable to significant degradation until the natural disturbance regimes are restored. Restoring natural disturbance regimes is, therefore, key in rewilding management (Torres et al., 2018) including to increase the resilience of the ecosystems to current and projected climate change (e.g., Kulakowski et al., 2017).

Domestic and semi-domestic livestock species can play an important role in the restoration of stochastic disturbance regimes, particularly in areas where wild large herbivore species are absent, as is often the case in areas with long-term and large-scale human pressure (Sandom et al., 2014a; Svenning et al., 2016). Until natural fire regimes have been restored, grazing by livestock could also limit the accumulation of fuel and thus lower the risk of wild and intense fires with risks to natural and human capital (Davison, 1996; Bruegger et al., 2016).

Dispersal and Connectivity

Dispersal is essential for the viability of wild populations, to increase access to ephemeral resources, facilitate recovery from disturbances, as well as to reduce inbreeding (Moseby et al., 2018; Perino et al., 2019). Dispersal by large herbivores also facilitates a range of ecological processes including pollination and seed dispersal (Corlett, 2013; Dirzo et al., 2014; Rey Benayas and Bullock, 2015). Where wild large herbivores have been lost from the landscape, it is important to ensure that the use of domestic livestock reproduces the movement patterns, large and small scale in space and time, of those wild species (García-Fernández et al., 2019). This can include active herding the ensures that ecological processes are restored or maintained. Nonetheless, land-use change and the fragmentation of landscapes, including due to linear infrastructure, greatly affect the size and integrity of habitats, thereby affecting the ability of individuals to disperse (Berger-Tal and Saltz, 2019).

Rewilding projects consider the restoration of the connectivity between patches of habitats, for instance by establishing corridors and making linear infrastructure more permeable and less lethal (Root-Bernstein et al., 2017; Torres et al., 2018; Perino et al., 2019). The restoration of dispersal can also be directly embedded within the human-dominated landscape, for instance by adding natural elements such as woodland islets in agricultural fields (Merckx and Pereira, 2015; Rey Benayas and Bullock, 2015). Furthermore, free-ranging livestock can play a role as seed dispersers (Bruun and Fritzbøger, 2002; Couvreur et al., 2004) and their trampling, as well as dung deposition, has been shown to contribute to germination, although with seldom discrimination between native and non-native species (Faust et al., 2011; Hogan and Phillips, 2011). Whether the ecological processes are restored by wild, semi-wild, or domesticated species, the ability of herbivores to disperse has implication for the viability (and welfare) of the populations, and their ecological role in the system Root-Bernstein et al., 2017; see Case study of Oostvaardersplassen below).

Trophic Complexity

Ecological theory supports the role of trophic complexity and trophic interactions in maintaining ecosystems, for instance *via* the regulation of populations sizes and distributions through processes such as predation and competition, as well as its impact on other processes such as disturbance and dispersal (Perino et al., 2019). The consequences of the degradation of trophic complexity is being increasingly witnessed and understood globally (Estes et al., 2011; Dirzo et al., 2014), particularly with the loss of large carnivores and large herbivores from ecosystems (Ripple et al., 2014, 2015).

An approach to rewilding illustrates the importance of trophic complexity i.e., "trophic rewilding" which places an emphasis on the reinforcement of populations, or on the reintroduction of missing species, particularly large carnivores and large herbivores (Svenning et al., 2016). However, in several cases, the restoration of complex trophic networks will not be possible because some species have gone regionally or globally extinct (Svenning et al., 2016; Fernández et al., 2017). Even when keystone species are only regionally extinct, public acceptance of their reintroduction might be low, e.g., European bison (*Bison bonasus*) (Decker et al., 2010; Klich et al., 2018), often due to a phenomenon known as the 'shifting baseline' syndrome, whereby the human expectation of what are 'good' or 'natural' environmental conditions is determined by the current experience rather than a historic diversity that is not present in living memory (Pauly, 1995; Manning et al., 2006; Papworth et al., 2009; Clavero, 2014). The case studies as presented below fall on a gradient from greater human intervention in the case of reindeer herding through to much lighter management input in the case of OVP and Knepp. This demonstrates how the approach we are presenting can be applied in different rewilding contexts.

In the case of the restoration of trophic complexity specifically, the potential of livestock is still limited. For instance, the extent to which livestock can be considered as a replacement for wild herbivores will depend not only on their functional role in herbivory and fire suppression but also on people's acceptance of depredation by wild predators on those domestic or semi-domestic populations (Bautista et al., 2019). However, we know a huge amount about the interaction between livestock and a broad range of natural ecosystems and this knowledge can be used in replacing extinct species disturbance regimes (Gordon et al., 2004).

Interacting Processes

The three ecological processes discussed above do not act in isolation and their interactions should be considered for rewilding. For instance, the natural recolonization or reintroduction of large herbivores, or the use of livestock as functional proxies for wild species, without control by natural predators could alter the natural disturbance regime within the landscape and lead to detrimental grazing impacts. The restoration of the spatial and temporal variability of the trophic interactions is also important to take into consideration in rewilding projects, for instance with the restoration of a "landscape of fear" (Manning et al., 2009; Suraci et al., 2016), and its impact on the spatial distribution of nutrient deposition and grazing pressure. The landscapes to be rewilded must also be sufficiently large, or connected, to allow the movement of predators and prey species. Predation, by stochastically distributing carcasses in the landscape, also plays an indirect role in both the size of populations of detritivores and plant growth *via* nutrient depositions (van Klink et al., 2020). While large carnivores are not yet part of the ecosystem, managers of rewilding areas should consider how to replicate these trophic interactions artificially (ICMO, 2006).

Ultimately, restoration is a societal vision for interactions between humans and nature, and the choice of given interventions and their likely outcomes. In the case of rewilding, approaches and outcomes can vary greatly depending on the historical baseline considered and the intensity of the action that one is willing to apply (Fernández et al., 2017). This explains why the interventions considered to date can range from letting wild species recolonize recently abandoned farmland (Navarro and Pereira, 2012), to the reintroduction of elephants (e.g., *Elephas maximus*) as proxies for the ecological role that mammoths (*Mammuthus* spp.) played in the landscapes of the Pleistocene (Donlan et al., 2006). This broad spectrum of interventions for rewilding also means that there is room to shift from considering that the role of livestock exclusively for food production and the maintenance of cultural landscapes, towards including their functional role into strategies for the short- or medium-term creation of self- sustaining and wild ecosystems.

GENERAL CASE STUDIES

Given the emphasis in rewilding is on restoring natural ecological processes, rather than species *per se* there is no logical reasons against using domestic animals or niche substitutes if they provide ecosystem functions, achieve the desired ecosystem state, and provide the same ecosystem services. This may be particularly important in the early stages of a rewilding project. However, using domestic livestock for rewilding has implications for both the nature managers and for the animals themselves; in the upcoming section we will outline four case studies, and discuss how they have used, more or less successfully, domestic animals for projects associated to rewilding. These examples inform and generalise guidelines for the use of domestic animals to restore or retain key ecological processes for rewilding. Here domesticated animals are meant as animals that are tame, have their reproduction controlled by humans and are dependent upon humans for their survival (Drenthen and Keulartz, 2014), and semi-domesticated are meant as animals who still need some human intervention for their survival, but have some autonomy in their movements. However, there is a continuum between wildness and domesticity that depends on the amount of human intervention and care given to the animals, but also on the adaptability of the animals to their environment (Keulartz, 2010). Hence, we advocate for the inclusion of domestic animals in the toolkit of rewilding projects and for the increased deliberative intervention of managers in cases where scale, type of animal or social context do not leave room for a large scale, hands-off rewilding approach.

Reindeer Engineer in Swedish Lapland

Our first case study explores the initiative, launched in 2015 by Rewilding Europe, Rewilding Lapland (since renamed Rewilding Sweden). It is a unique project to encourage a new economy based on the cultural landscape of Saami and the Laponia region, that stretches over the north of Sweden and Norway. The area is populated by the First Nations Saami people and herding of semi-domesticated reindeer (*Rangifer tarandus*) is an essential part of their culture and has shaped the landscapes for generations. Reindeer herds wander freely in unfenced areas between foraging in the tundra during the snow free season and spend the winter in the boreal coniferous forest where they feed on lichen, thereby limiting the need for supplementary feeding. Comparably to other indigenous populations elsewhere in the world, the relationship of the Saami people with the Swedish State is complex and there is a long history of State repression of cultural activities (Lantto and Mörkenstam, 2008). Today, tensions are mostly with the forestry sector, representing a powerful industry that intensively manages forest plantations in Laponia. The region also includes the Laponia World Heritage area, which comprises large areas of old growth forest and stands as a symbol of co-management of natural resources between the Saami and the Swedish State (Reimerson, 2016).

The Rewilding Sweden project seeks to create an economy based on the unique socio- ecological system that includes Saami culture, wildlife, and free flowing rivers (Koninx, 2018). Reindeer and reindeer herding are an essential part of this nature-culture landscape, influencing landscapes through their grazing and trampling. In turn reindeer are connected to the semi- nomadic herders who engage in transhumance with the reindeer herds (Rouet-Leduc and von Essen, 2019). Reindeer are an important source of income for reindeer herders, in terms of meat products but also products derived from the reindeer skin, antlers, etc. as well as tourism activities related to reindeer (Koninx, 2018). The path followed by Rewilding Europe (2020) generally is a bottom-up, network-based approach putting Saami knowledge and cultural relationship with nature at the heart of the vision for the new economy, with reindeer being the most important keystone species of the area because of their disproportionately large impact of the ecosystems compared to their abundance (Paine, 1966; Power et al., 1996). The Rewilding Sweden project promotes a network of nature conservation actions, with a focus on reindeer herding and river catchments, valuing pre-existing human-modified systems using semi- domestic reindeer. In this context, rewilding with predators or wild herbivores could create great disruption in the reindeer herding activities, since predator presence creates a major issue for herders (Sandström et al., 2009), and other wild herbivores are likely to compete with the reindeer for limited forage resources. Recognising reindeer as the keystone species of the area, despite it not being a truly wild animal, allows for a "relevant and minimally respectful compromise" to be made as the animal is at the heart of Saami livelihood and tradition (Rouet-Leduc and von Essen, 2019).

In Rewilding Sweden, approval from local, and especially Saami, communities is especially crucial; therefore, synergising the interests of reindeer herders and other issues of nature conservation allows for the creation of a long-term, large-scale project that has a social licence to operate. In contrast with the intensive forestry activities that occupy major areas of Swedish Laponia region, the project's approach is based on common interests in preserving wild areas (Widmark, 2009), since reindeer herding, like rewilding projects, depends on restoration or protection of wild nature, in this case old-growth forest.

Livestock Fire Brigade and Free Running Horses in the Côa Valley, Portugal

The Faia Brava reserve in Portugal, illustrates how the use of domestic livestock and human management is necessary, either as a transition period towards future "self-willed" wild nature, or because of other limitations that requiring cognisance of animal welfare, human-animal relations, or legislation.

In recent years, the Mediterranean region of Europe has seen a rise in the abandonment of farmland and traditional land management practises. This transition has led to shrub encroachment, increased fuel load (because domestic herbivores are no longer removing biomass and populations of wild herbivores are still relatively low), increasing the risk of wildfires (Moreira et al., 2011). This land abandonment process takes place on former traditional landscapes such as the Montado/Dehesa silvopastoral systems in Portugal and Spain that combine silvicultural activities, usually of cork oaks (*Quercus suber*), with agriculture and extensive grazing (Oteros-Rozas et al., 2014; Godinho et al., 2016). In the North East of Portugal, the Côa Valley is a textbook example of the rural exodus leaving large swathes of disused agricultural areas. The Portuguese Non-Governmental Organization Associação Transumância e Natureza (ATN), together with the support of the European organization Rewilding Europe, has established a reserve on former agricultural land, Faia Brava. The area was previously used for olive (*Olea europaea*), cork (*Quercus suber*), and almond (*Prunus dulcis*) groves, as well as extensive herding of goats and sheep (DeSilvey and Bartolini, 2019). The reserve, created in the 2000's, is now home to semi-wild Garrano horses (*Equus ferus caballus*) and cattle (*Bos taurus*) herds.

For several reasons, Faia Brava illustrates well the use of domestic animals and the human intervention in rewilded landscapes. The size (about 850 ha), as well as the nature of the reserve being situated in a highly anthropogenised landscape with a strong cultural value, calls for multiple human interventions to maintain the reserve and the animals that are present in it, creating a natural and cultural landscape of co-habitation and co-production (DeSilvey and Bartolini, 2019). As well as being limited in size, the reserve is surrounded by land that is still used for agriculture and pastoral activities. Therefore, a completely hands-off approach is not possible, and some level of management of the animals is necessary, to avoid human-animal conflicts and to meet requirements for animal welfare. The horses and cattle, therefore, receive supplementary feeding, especially in the years with harsh conditions, and have access to artificial water points in the reserve. Also, due to the near absence of predators in the area, managers of the reserve mimic predation and maintain populations of animals at a level they judge to be in accordance with carrying capacity of the area. In theory, the number of animals could be regulated bottom-up by the amount of food available, similarly to the initial management practises at Oostvaardersplassen, but the need for public acceptance requires human intervention in regulating populations of animals, to avoid public outrage in the absence of regulation by predators. Excess cattle are sold for meat while horses are sold as pets.

The management of the horses and cattle in the reserve is made easier by the relative tameness of the animals. Rewilding Europe aims at having a "self-sufficient wild bovine grazer" in multiple places, including Faia Brava, as part of their Tauros program but in this long transition phase, the cattle are still managed. The "back-breeding" process used in the Tauros project, selects traditional local breeds like the Maronesas and Sayaguesas cattle, and seeks to eventually bring back a functional relative of the extinct auroch (Goderie et al., 2016; Rewilding Europe, 2020), although we would assert that this is not necessary given that hardy domestic breeds are available.

In Faia Brava, as with all rewilding projects, social context must be taken in to consideration, in terms of social preference as well as nature's contribution to people's lives and livelihoods in the form of ecosystem services (Perino et al., 2019). The successful annexation of the reserve was dependent on good relations with both regional authorities and local inhabitants. The use of semi-wild animals made their management easier but the continuous existence of traditional herding of cattle and sheep (*Ovis aries*) in the area made the relationships with herders a challenging cooperation (Pellis, 2019). In these post-agrarian landscapes (Lorimer and Driessen, 2016), transition is a lengthy process and requires cooperation across the traditional agricultural and rewilding sectors.

An important aspect that characterises this project is the will to involve and include the local community in deriving benefits from the reserve. This creates nature-based economic activities, as an alternative to land abandonment (with its associated reduced economic opportunities), as well as encouraging social acceptance of the rewilding project. Rewilding Europe and ATN have been actively collaborating with the local community, especially the local shepherds and the inhabitants of the neighbouring village of Cidadelhe (Pellis, 2019). The Faia Brava reserve is already home to ecotourism activities, based on wildlife viewing and other nature-based activities related to the area. Rewilding Europe is also emphasising the nature-culture aspects of these enterprises by combining the allure of the rewilding project with the broader benefits of the location in the Côa Valley, which is listed as a UNESCO World Heritage Site, for its Prehistoric rock art depicting large herbivores (UNESCO, Rewilding Europe). More generally, managers of rewilding projects are aware of potential tensions that their vision of future landscapes can spark in traditional agrarian landscapes, where the culturally-based assumptions for how landscapes should be managed do not necessarily match with rewilding projects. Reconciling different management paradigms is a challenge which justifies, in the Faia Brava case, the use of semi-wild (or semi-domestic animals), that are similar to the domestic animals present in the area and are, therefore, more familiar and acceptable to the people living in the area. This case study, therefore, shows that, because of the strong cultural aspects and the omnipresence of traditional agrarian activities and cultures, rewilding must happen within a socially acceptable operating space that identifies and respects societal norms (Corlett, 2016; Perino et al., 2019).

Ecotourism and Sustainable Meat at Knepp Estate, England

The Knepp Estate in England is one of the most famous examples of rewilding in Europe, stretching over 1,400 ha of former farmland, and home to numerous wild-living herbivores, such as longhorn cattle, Dartmoor horses, red (*Cervus elaphus*) and fallow deer (*Dama dama*) and Tamworth pigs (Tree, 2018). While it is using some domestic species, the vision for the Knepp Wildland project is to create a rewilding area, that is not determined by the conservation of a specific species or habitat, but rather by the restoration of natural processes and the use of large herbivores as keystone species to achieve this vision. In just two decades, since the Knepp Wildland project began, the estate has seen a remarkable restoration of biodiversity, including rare species like the purple emperor butterfly (*Apatura iris*) and the peregrine falcon (*Falco peregrinus*).

The Knepp Wildland project started as a rewilding experiment on impoverished farmland and is now seen as an example of successful land management, and also a good case of nature-based economy. Indeed, the Estate is both an important place for ecotourism with its relative closeness to London, and it also produces around 75 tonnes of "wild" organic meat per year. The Knepp Wildland project started in 2001 and aims at creating a rewilding area with naturalistic grazing acting as a model for rewilding agricultural land in the UK (Overend and Lorimer, 2018). Considering the size of the Knepp Wildland, and the fact that there are no predators of large herbivores in the area, animal numbers must be controlled artificially. The domestic breeds such as longhorn cattle and Tamworth pigs are culled for the meat market, while deer are culled by stalking. Additional management is required by regulations, meaning that all the animals, except for the deer, must be registered, taken care of, and slaughtered in accordance with national legislation. The livestock, even though feral are managed so as not to pose a threat to humans and are not "too" wild (Rotherham and Handley, 2011) to keep public support for the project. Knepp Wildland has developed a broad range of activities based on rewilding that provides an alternative income to using the land for agriculture purposes. For example, the Estate sells sustainable premium meat from the longhorn cattle, the Tamworth pigs, as well as different types of venison from the deer. It focuses on the meat products being "wild range meat", and the fact that the meat comes from ancient breeds and that the animals have lived and fed in a "wild" environment is a selling point. Also, the Estate offers numerous opportunities for recreation, such as wildlife watching and safari-like excursions.

The Knepp Wildland project is an excellent illustration of how domestic breeds of livestock can be included in the toolkit of nature managers in rewilding projects. As keystone species the animals perform specific roles in shaping the landscape, providing multiple ecosystem services including habitat for biodiversity, while also giving an economic return in the form of premium wild meat and ecotourism. However, in other circumstances there may be social and ethical issues associated with the harvesting of animals in rewilding projects (as has been discussed for wildlife species, see Thulin and Röcklinsberg, 2020).

Oostvaardersplassen: The "Wild Experiment"

Oostvaardersplassen (OVP), in South Flevoland in the Netherlands, is one of the most famous, influential but controversial, rewilding projects in the world (Lorimer and Driessen, 2014a). It was established on a reclaimed polder, originally intended for industrial development, but due to economic downturn in the early 1970s, was instead turned into a nature reserve (Vera, 2009; Lorimer and Driessen, 2014b). The reserve is about 6,000 ha of wetlands, grasslands with some trees and shrubs, surrounded by human dominated landscapes (intensive agriculture, urban fabric) with no connectivity to other (semi-)natural areas. This means that populations of large herbivores are not only not top-down regulated, but they can also not disperse. The site has become a very important habitat for birds, with over 78 species recorded (Schwartz, 2019). Species such as spoonbill (*Platalea leucorodia*), bittern (*Botaurus stellarus*), marsh harrier (*Circus aeruginosus*) and bearded tits (*Panuris biarmicus*), all previously rare in the Netherlands, established there (Vera, 2009). Also, bird species that were completely extinct as breeding species in the Netherlands established including the graylag goose (*Anser anser*), great white egret (*Ardea alba*) and white-tailed eagle (*Haliaeetus albicilla*) (Vera, 2009). Over 30,000 greylag geese over-winter there and influence the ecosystem through their grazing (Vera, 2009).

To avoid willow (*Salix cinereal*) encroachment onto grasslands two large de- domesticated forms of herbivore species were introduced in the mid-1980s, i.e., Heck cattle (*Bos taurus*) and konik horses (*Equus ferus caballus*). Red deer were introduced in the 1990s. These introductions were also underpinned by an alternative theory of past forest dynamics in which it was argued that ancient forests were more open than previously assumed, because of herbivore grazing and browsing (Vera, 2000). Critically, the herbivores were to be "unmanaged" and live as wild (i.e., free mate choice, social structuring) with population numbers being determined by food availability in the winter (Vera, 2009). As such, there were "no targets, no models and no explicit action plan" (Lorimer and Driessen, 2014b, p.48), which was a major divergence from mainstream conservation practise and regulation. The fact that the land was reclaimed from below sea-level, perhaps provided greater flexibility in thinking and experimentation with the focus on nature and natural processes ("new wilderness"—Schwartz, 2019), rather than the more traditional guided conservation management pathway towards a past or pre-determined state. Critically, the reserve is surrounded by human dominated landscapes (intensive agriculture, urban fabric) with no connectivity to other semi-natural areas.

From the initial introduction of founders (32 Heck cattle, 18 Konik horses and 40 red deer), the populations grew to over 5000 individuals, and the philosophy meant there were no prescribed targets (Schwartz, 2019). This meant that animals would die of starvation in tough winters (though rangers would proactively cull animals that were suffering), and carrion would provide food for predators including white-tailed eagle (Vera, 2009; Schwartz, 2019). This approach was controversial and challenged in court but was permitted to continue with some recommended changes (Vera, 2009; Theunissen, 2019). Though a review in 2006 noted that "the public preference for avoiding OVP management policies that involve the routine culling of substantial numbers of healthy animals" (ICMO, 2006, p. 7), indicating divergence in community views on the management principles. However, during a harsh winter in 2017 over 3,000 (∼60% of the population) animals were euthanized or died of starvation. There were public protests, and people illegally threw bales of hay over the fence surrounding the reserve (Schwartz, 2019). The provincial authority of Flevoland reviewed the management of the large herbivores (van Geel et al., 2018) and changed the management regime to set target populations sizes (210 Heck cattle, 550 Konik horses and 500 red deer). The populations were to be managed through active control and relocation to other projects. There was also a stipulation that each individual herbivore should be sighted three times a week, its condition assessed, and veterinary attention provided if needed (Schwartz, 2019). The changes effectively ended the "self-willed" management of the herbivore population. There was perhaps, a missed opportunity, following the earlier review of management in 2006 by independent large herbivore experts at a time when public opinion appeared to have supported the novel management regime, but issues were emerging (ICMO, 2006). They outlined a range of alternative management scenarios: (1) no intervention (2) proactive culling or removal (3) reactive culling (4) contraception. They recommended proactive culling or removal to minimise starvation and winter mortality *but* suggested these could be designed to mimic natural processes by (i) simulating the impact of natural predation and episodic mortality; (ii) removal of a fixed level of annual recruitment – but that range could be varied according to ecological carrying capacity; and (iii) removal of a variable numbers of animals each year based on body condition (ICMO, 2006). This recommendation allowed for a more nuanced, naturalistic management regime than eventuated in van Geel et al., 2018, when public opinion appeared more fixed against the original principles. This outcome serves as an important reminder of the need to consider the interaction of the society and ecology when defining management goals for rewilding (while at the same time recognising that all outcomes cannot be predicted at the outset).

There are many lessons from the Oostvaardersplassen "wild experiment"—these are not just ecological, but also social, philosophical and theoretical. Although it has been criticised as a "failure" by some (e.g., Theunissen, 2019), given it was largely experimental, and the outcomes of the novel approaches were not known *a priori*, it is perhaps unfair to apply measures of success retrospectively. While it may have failed by some perspectives, it has allowed the exploration of the principles of rewilding, and the relationship between this process and the public (i.e., social licence), and arguably helped to propel the broader rewilding movement to where it is today—on the cusp of becoming mainstream (Bakker and Svenning, 2018; Pettorelli et al., 2018, 2019).

Oostvaardersplassen raises important questions about the definition of rewilding, or rather whether there should be accommodation of different types of rewilding. At its core is a debate about human intervention—how much, when and what? Some of the criticism of Oostvaardersplassen has been that the area was too small and there was no natural predation

(Schwartz, 2019) —though noting that Vera (2009) argued that evidence from Africa suggested bottom-up processes (i.e., food availability) would naturally drive the majority of mortality, and, therefore, overwinter deaths were to be expected. Therefore, in order to maximise the level of "self-willed" properties and processes, should human intervention be considered (can it be avoided?) in some parts of the ecosystem? —at least in the establishment stages? At the same time, it is likely that rewilding projects will want to avoid succumbing to the previous constraints (Butchart et al., 2010; WWF, 2016; IPBES, 2019; indeed many of the cumulative failures, e.g., at a global scale) of more mainstream "command and control" resource management (*sensu* Holling and Meffe, 1996). In short, and perhaps counterintuitively, is deliberative, measured, targeted intervention the price that must be paid to have rewilding at a broadscale?

The introduction of population targets at Oostvaardersplassen in 2018 raises some interesting research questions and highlights an opportunity. Firstly, is it necessary to have to intervene in herbivore populations, as a price for having "rewilded" populations and ecosystems? How can evidence-based offtake targets be derived based on assumed bottom-up and top-down (predation) pressure? How do managers mimic natural mortality to maintain the ecological and evolutionary processes that are desired? The ICMO (2006) provided some valuable suggestions of how this might be achievable. The Heck cattle and Konik horses of Oostvaardersplassen had been under bottom-up selective pressure since the mid-1980s, but how will the culling towards the new targets change selection pressure across the population? Secondly, the combination of annually determined harvest levels, but the continuation of otherwise "wild" life history of the large herbivores, potentially opens the possibility of an integrated rewilding-farming model that markets the meat of the harvested animals, as in the case of the Knepp Wildland project above. Such products could be branded as supporting the rewilding of these extensive ecosystems and all of the co-benefits seen at Oostvaardersplassen [though we are not advocating this for Oostvaardersplassen, rather the concept, noting that using culled animals for human consumption was floated in the ICMO (2006) review]. The benefits of such a model are that the potential for financial feedback means more farmers could consider this as an alternative model for their land management, and, therefore, more land could operate under rewilding principles. In essence, this could be a Knepp+ or Faia Brava+ model in which feral livestock and wild herbivore species live as wild for their full life history (i.e., "self-willed"), but are monitored to meet societal expectations for their welfare and harvested to manage population size and to fund rewilding activities that would otherwise not take place.

CONCLUSIONS

Rewilding, as a conservation practise, is regularly criticised for being the subject of internal disagreement regarding its definition (Lorimer and Driessen, 2014a; Jørgensen, 2015; von Essen and Allen, 2015). The idea of using domestic animals in rewilding projects can appear to be in opposition to some of the core definitions of rewilding, inasmuch as the term of rewilding involves restoration of "self-willed" nature or the "autonomy of the more than human world" (Jørgensen, 2015; Prior and Ward, 2016). We argue, however, that a lighter version of rewilding, *rewilding lite* if you will (Carver, 2014), allows for the use of livestock in support of these broad objectives. To re-emphasise, this is not restoration dressed up in sheep's clothing but still has at its heart the core outcomes of rewilding but through a different mechanism of reinstating lost processes.

It is still early days for the rewilding agenda within conservation science and practise. However, there are large areas of historic research that can be brought to bear in support of the outcomes that are the philosophical underpinnings of the approach (e.g., conservation/ecological sciences, agricultural research, community-based conservation). From this, key lessons can be applied in the new context of rewilding. Firstly, there must be clear statements of the objectives for any rewilding project, and a plan (preferably based upon a theory of change) to get to the outcome. Just 'letting nature take its course' is not likely to be enough in many situations and can be a derogation of the duty of those responsible for the project. Not doing anything is a management decision in itself and must be assessed in the same way as interventionist options. In the early stages of a rewilding project, it is likely that the management interventions will be required, and the manager is best served by having a broad range of options in the toolkit. These should include the opportunity to use livestock to remove vegetation (native and invasive) and change vegetation structure in support the improvements of biodiversity or the provision of ecosystem services on the site. Secondly, attempts to de- domesticate livestock to create facsimiles of ancient breeds may not be necessary if the goal is to facilitate ecological process for rewilding. The desire to create an animal that looks like a lost species, such as an auroch (Stokstad, 2015; Goderie et al., 2016), should not be conflated with the goal of finding an animal that returns lost processes. The reconstruction of the facsimile of extinct species is fraught with challenges and may lead to animals that are more needy than their constituent ancient breeds [e.g., Heck cattle appeared to be susceptible to competition from other grazers which impacted the cattle's condition; ICMO (2006)]. Indeed, there is a circularity in the logic of the process of de-extinction given that creating such a species depends on existing hardy breeds as founders—which raises the question why not just use the hardy breeds? Selective breeding to create facsimiles also assumes humans can pick traits through selection that confer adaptive advantage in the wild better than does natural selection. For example, an unintended consequence of the new management regime at Oostvaardersplassen may be ceasing natural selection and de-coupling of animals from the ecosystem—because natural selection of cattle, horses and deer has, largely, been replaced with human selection (the antithesis of rewilding). It may instead be more effective to use existing hardy breeds bred by humans for many generations to thrive in regional conditions, or to establish a rewilding project with a mix of livestock breeds and let selection evolve a locally adapted wild breed. Having

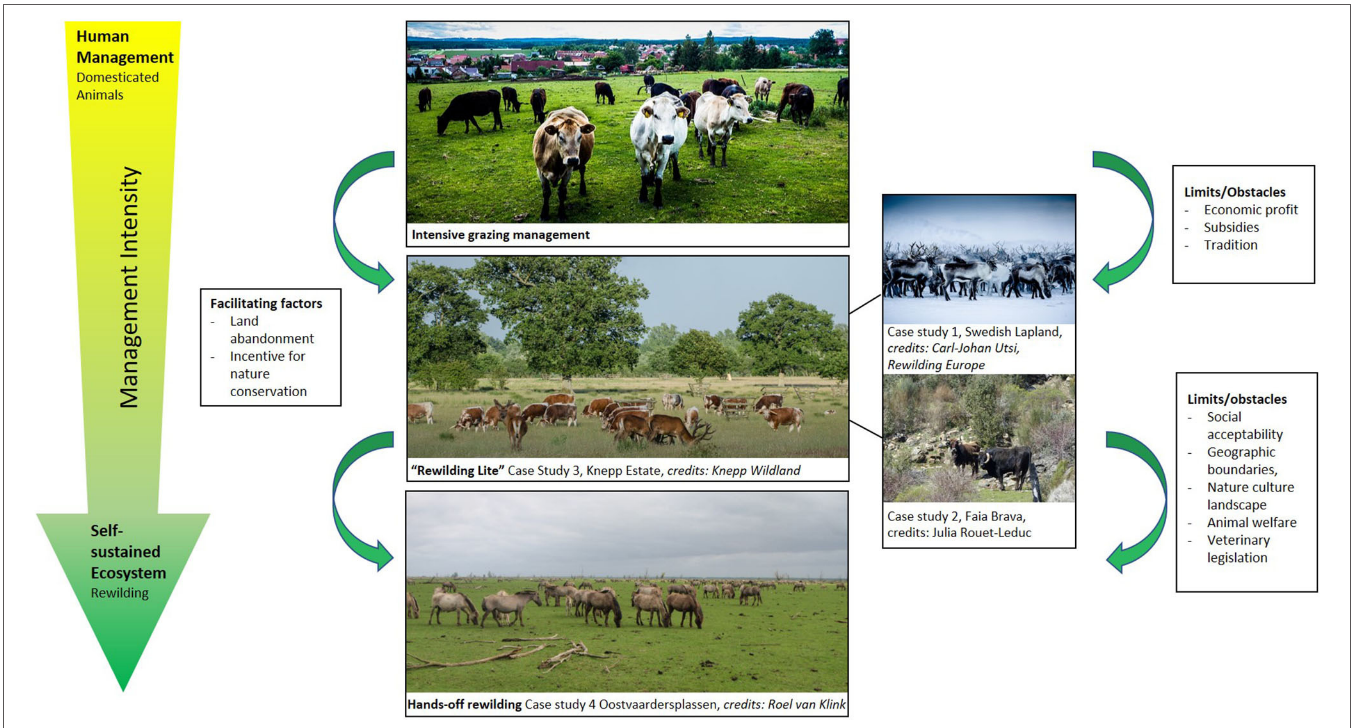

FIGURE 2 | Schematic representation of how different types of land managements with large herbivores are facilitated or hindered by different factors. Our case studies are all situated within the second type of land management, that is rewilding with domestic animals. The top panel represents traditional rearing of animals with high management intensity, and the bottom panel represents "hands-off" rewilding (i.e. "rewilding max") with minimal human intervention, in this case Oostvaardersplassen.

said that, the new suit of gene editing techniques may help offer an alternative route to bringing back extinct species in the future (Richmond et al., 2016). Thirdly, except in exceptional circumstances, rewilding projects do not sit in isolation from the broader socio-economic system of the region, country, or continent (even though the approach appears to be setting nature in juxtaposition to humanity). There is, of course, the real risk that rewilding becomes tarred with the same brush as the 19th- and 20th-century approach called fortress conservation that attempted to isolate nature from people's impact by removing indigenous communities and only allowing access to the elites (Dowie, 2009). As such, from even before the inception of the rewilding project, mechanisms need to be in place to ensure that the broader community is on board with the project and ideally is invested in the project. Particularly, traditional livestock keepers (i.e., pastoralists, herders and farmers) could have an important role to play in broad-scale rewilding rather than being opposed to it. This is for instance the approach taken by Rewilding Europe when designing and establishing a rewilding project together with local populations (Helmer et al., 2015). Finally, linked to the third point, but separate from it, in its purest form rewilding posits people as external to the restoration of ecological processes. First Nations people have been engaged in the management of ecosystems for generations, and the keeping of livestock, both domestic and semi-domestic for millennia; First Nations people should, therefore, be encouraged to initiate rewilding projects and be central to the development of project across the continents of the planet. This socio-ecological systems approach should, in our view, be foundational to rewilding philosophy and practise.

The case studies outlined above represent points on a rewilding continuum for the role that semi- domestic, domestic livestock could play in rewilding projects (**Figure 2**). In the case of the semi-domestic reindeer herds of the Saami First Nations people in northern Scandinavia (Rewilding Sweden), the transition to support rewilding objectives requires very little change to the management regimes. For Knepp and Faia Brava the removal of inputs through, energy, labour, and fertiliser/irrigation were key to meeting the objectives, however, clarity is required on what ecological process states are the intended outcomes of the rewilding project. If these entail removal of vegetation, or the maintenance/creation of open areas within potentially wooded/forested landscapes, then grazing is an effective way of achieving this over large areas. If there are constraints (management, social, economic, environmental, regulatory, welfare) to the use of wild herbivore species then domestic livestock species are a potential option. When livestock species are used, be they semi-domestic or domestic, there will be a requirement for intervention in most situations (the same is the case for wild species where predators are not present in the system). These interventions will depend upon the local circumstances but are likely to include aspects of livestock husbandry required to meet environmental, biosecurity, legal and welfare objectives. The Oostvaardersplassen example, demonstrates the need for such measures to be put in place early so that public support for the rewilding project is not compromised.

In some cases (as exemplified by Knepp Wildlands) money can be generated from harvesting livestock products, but it should be noted that this would be counter to the original principles of rewilding if this were the primary reason for the husbandry activities. So, the offtake of products needs to be a byproduct of delivering the rewilding outcomes. The degree to which livestock are managed will vary depending upon circumstances, however, the introduction of a safe operating space (c.f., Rockström et al., 2009) could be incorporated into the rewilding principles. In this paradigm managers can be hands-off whilst the system fluctuates within a set of predefined boundary conditions (though these will be broader than those in traditional agriculture and conservation), be they structural or process-based; however, interventions will be brought to bear when the system is at risk of moving beyond those boundaries (see also Corlett, 2019). In effect, this is what happened in the case of Oostvaardersplassen, however, it was not formally incorporated into a management plan until after the project had run into severe public relations problems. The safe operating space will, therefore, incorporate a component of the socially acceptable operating environment (social licence to operate) as defined by the community of engagement with the rewilding project. Obviously, there will be ecological and evolutionary consequences of this approach, that will play out in the wild and livestock species within the system.

In conclusion, we see the potential benefits of including species of domestic and semi-domestic livestock in the toolkit of managers responsible for rewilding. This will require a re-conceptualisation of the characteristics of rewilding and/or rewilded landscapes, along with release from some of the policy/regulation constraints imposed on feral/free-living livestock (Hall et al., 2005), and changes in attitudes, across all sectors engaged in this thought-provoking and forward-looking approach to the engagement between nature and people.

AUTHOR CONTRIBUTIONS

IG, LN, JR-L, and AM conceptualised the overall theme of the manuscript and wrote the manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2021.550410/full#supplementary-material

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Goat Grazing for Restoring, Managing, and Conserving "Satoyama", a Unique Socio-Ecological Production Landscape

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Agricultural intensification and socioeconomic changes over several decades have generated many abandoned fields. These changes have led to reduce plant and animal biodiversity, as well as associated loss of ecosystem services, and represent deterioration of a unique socio-ecological production landscape known as "Satoyama" in Japan. Appropriate management measures should be implemented to restore these abandoned fields. The objectives of this study were to: (1) determine the effect of goat grazing on vegetation dynamics and animal performance in response to different stocking rates over a 5-years period; and (2) evaluate the economic potential of weed management through goat grazing by comparing this method to mowing with a brush cutter. We found that goat grazing changed vegetational composition, increased the number of plant species, and improved plant diversity in the abandoned field, although stocking rate had little effect on plant diversity. Goat grazing changed vegetation quality, even though goats maintained their nutritional status and body weight over 5 years. Goat grazing showed economic advantages over mowing during a relatively short period (up to 8–12 days per 1,000 m^2). Overall, we found that goats would be ecologically and economically useful in restoring, managing, and conserving agricultural fields. However, a more comprehensive approach is still necessary for conserving "Satoyama." Combination of grazing, mowing with a machine and prescribed burning may be more effective, and animal and biofuel production in these field would be a solution for reducing field abandonment.

Keywords: abandoned field, economic potential, goat, grazing, restoration, Satoyama, weeding

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INTRODUCTION

Satoyama is a unique socio-ecological production landscape composed of a mosaic of paddy fields, secondary forests, grasslands, ponds, and streams that create and provide various habitats to many plant and animal species in Japan (Washitani, 2001; Katoh et al., 2009). However, agricultural intensification and socioeconomic changes over several decades have induced outflow and aging of rural population who manage this production landscape. These changes also have decreased economic incentive to use marginal agricultural field, resulting in many abandoned fields in this area. Since the mid-1970's, the area of abandoned field in Japan have increased and it is currently over 400,000 ha. More than half of these areas are now considered unsuitable for paddy and crop farming (Ministry of Agriculture Forestry Fisheries, 2018) due to encroachment and overgrowth of weedy and shrubby plants. Typical dominant species in an abandoned field are bamboo (*Phyllostachys edulis, P. bambusoides*, and *P. nigra var. henonis*), dwarf bamboo (*Pleioblastus argenteostriatus* f. glaber, *P. chino* Makino, etc.), Kudzu (*Pueraria montana var. lobata*) and other alien species such as tall goldenrod (*Solidago altissima*). These plants spread to an abandoned field by vegetative growth or anemochory from neighboring forests and fields. In the past, these weedy and shrubby plants have been removed by human mowing with brush cutter and other machines. However, labor shortage in rural area makes it difficult to use this approach. Thus, appropriate and alternative management measures should be implemented to restore and utilize these abandoned fields.

Grazing may be a feasible way to manage these abandoned fields (Hall, 2018) as herbivores prevent encroachment and overgrowth of weedy and shrubby plants (Popay and Field, 1996). Goats eat more shrubby and woody plants than cattle and sheep and may thus be effective weed managers (Animut and Goetsch, 2008). Moreover, goats can survive in nutritionally harsh environments because of their ability to eat a wide range of plants and their low metabolic requirements, and they are capable of grazing and moving in hilly and steep marginal areas.

Abandoned fields are typically composed of semi-natural vegetation, which is often lower in nutritional value than sown plant species. Moreover, vegetation and animal performance are largely influenced by stocking rate; long-term grazing at different stocking rates induces qualitative and quantitative changes in field vegetation, leading to differences in animal performance and affecting sustainable grazing in the management of abandoned fields. Furthermore, the economic potential of controlling weeds through goat grazing should be evaluated, because economical sustainability is also crucial to promote the dissemination of goat weeding as a strategy to restore abandoned fields.

In this short report, we present the quantitative and qualitative dynamics of vegetation and goat performance in response to different stocking rates over a five-year period. Then, we discuss the economic potential of weed management through goat grazing by comparing this method with human mowing with a brush cutter. Understanding these dynamics will facilitate the use of sustainable goat grazing systems to maintain the unique "Satoyama" landscape and its biodiversity.

MATERIALS AND METHODS

Field Study

This study was approved by the Committee for Animal Research and Welfare of Gifu University (#13022, 15020, and 17034). The study was conducted in a 0.8-ha abandoned field (35°29′ N, 137°1′E, alt. 130 m) mainly dominated by bamboo (*P. edulis*) for many years after abandonment. Shiba × Saanen crossbreed goats (16–17 goats with initial mean body weight (BW): 26.3 ± 8.0 kg at the start of grazing) were used for this study. Before the start of this study, the bamboo was clear-cut; then, the site was divided into two areas in which two stocking rates, high (HS: 30–33 goats/ha) and low (LS: 14 goats/ha), were implemented for 5 years. Generally, animal and vegetation measurements were conducted each year in spring (late May), summer (late July), and autumn (mid September to early October); however, those in the 1st year were 1 month later because of a month delay of the start of grazing. Plant biomass was estimated in six random plots (50 cm × 50 cm/plot) from each stocking rate; edible parts were collected for chemical analysis. Botanical composition was estimated in 20 fixed plots (25 cm × 25 cm/plot) at each stocking rate and was classified into forbs, Poaceae, Cyperaceae, shrubs, bamboo, and dwarf-bamboo (*P. argenteostriatus*). Forage intake by goats was estimated using a double-indicator method with *n*-alkane (Dove and Mayes, 2006) and acid detergent insoluble ash (ADIA: Nakano et al., 2007). Each *n*-alkane capusel (C_{32}) was administered to five goats in each stocking rate twice a day for 2 weeks. Then, fecal grab samples were collected from the rectum of the goats twice a day in the latter half of the weeks. Dietary *n*-alknae and ADIA contents were estimated by the combination of monitoring foraging behavior and hand-clipping. Foraging behavior of four goats (two goats/day) was observed for 2 h in the morning and evening feeding bouts. The top 9–10 plant species in their ingestive bites (∼80–90% of the total bites) were collected by simulating feeding behavior. Forage dry matter (DM) intake was estimated as follows:

DM intake (kg DM/day) = (fecal output [kg DM/day]/(1–digestibility)

Fecal output (kg DM/day) = C_{32} dose rate (mg/day)/C_{32} fecal content (mg/kg DM)

Digestibility = (1–[ADIA g/kgDM in diet]/[ADIA g/kg DM in feces])

Goats were weighed at the start and end of each investigation period. Forage intake and daily gain (DG) were analyzed using a generalized linear mixed model. Individual goat was assumed as a statistical unit. Botanical and chemical compositions were not analyzed statistically, because we just have one study site in each stocking rate.

Estimation of Economic Potential

A simple simulation study was conducted to compare weeding cost by goat grazing and human mowing with a brush cutter. The weeding area was set at 1,000 m^2, and weeding was conducted twice during May–November. Cost for human weeding with a brush cutter included cost for weed cutting, removing, and disposal, and the cost of each process was estimated following the cost estimate standards for civil engineering work (Ministry of Land Infrastructure Transport and Tourism, 2017); with this, the total cost for human weeding was estimated at 76,400 yen (685 US dollar)/1,000 m^2.

Cost for goat weeding was estimated using seven goats (to simulate a real-life situation) and the following equation:

$$Fee\ for\ using\ a\ goat\ (yen/day) = [(Pc - Cp) + Wyr \times (AMc + Oc)] / \left(Wyr \times Wday\right),$$

TABLE 1 | Changes of botanical composition during 5-years grazing at different stocking rate in an abandoned field.

Cover (%)	Type	2013			2014			2015			2016			2017		
		Spring	**Summer**	**Autumn**	**Spring**	**Summer**	**Autumn**	**Spring**	**Summer**	**Autumn**	**Spring**	**Summer**	**Autumn**	**Spring**	**Summer**	**Autumn**
High Stocking Rate																
Bare ground and litter		23.8	44.6	43.3	41.3	40.4	38.0	7.4	20.8	23.5	17.8	21.1	14.1	14.8	19.4	15.6
Bamboo *Phyllostachys edulis*	Grass	18.8	22.7	14.0	1.7	7.0	3.0	3.7	12.2	3.8	7.9	15.6	9.9	6.9	16.5	11.9
Dwarf bamboo *Pleioblastus argenteostriatus*	Grass	0.0	1.2	0.8	5.0	0.7	1.6	1.6	1.2	1.0	1.0	2.5	2.3	4.9	4.9	3.1
Other grasses *Poacea* spp.	Grass	4.9	7.0	11.5	10.9	12.3	12.5	26.4	19.5	17.5	16.0	20.8	21.3	18.2	24.1	23.0
Cyperaceae *Cyperaceae* spp.	Sedges	7.0	8.0	5.0	0.0	4.9	0.8	2.1	2.8	3.5	6.0	6.8	6.3	3.9	2.3	5.6
White clover *Trifolium repens*	Legume	7.2	1.3	1.0	2.7	4.0	0.5	2.7	2.0	0.0	1.0	0.6	-	1.9	0.7	0.1
Other legumes *Fabaceae* spp.	Legume	1.5	0.8	0.3	2.3	0.3	0.1	4.8	2.9	3.1	4.2	2.3	3.3	12.6	3.1	2.9
Tall goldenrod *Solidago altissima*	Forbs	16.0	4.0	0.5	2.8	2.5	1.0	2.7	-	2.9	3.9	0.6	0.8	0.3	-	-
Fish mint *Houttuynia cordata*	Forbs	3.0	0.0	0.7	0.0	0.3	0.1	1.3	3.2	3.0	4.1	8.8	7.2	7.8	12.3	14.7
Other forbs	Forbs	16.0	8.0	22.1	28.5	27.3	41.6	45.2	33.6	39.6	35.5	19.2	30.8	28.6	15.2	21.6
Shrubs	Shrubs	1.8	1.8	0.8	4.8	0.3	0.8	2.1	1.8	2.1	2.6	1.7	4.0	0.1	1.5	1.5
Low Stocking Rate																
Bare ground and litter		34.1	51.4	51.2	40.1	42.3	42.8	26.0	26.1	24.0	14.5	17.0	18.3	10.3	17.9	22.1
Bamboo *Phyllostachys edulis*	Grass	7.5	11.5	10.7	0.0	9.0	7.4	6.4	8.7	3.4	7.4	10.8	10.6	2.3	9.6	8.1
Dwarf bamboo *Pleioblastus argenteostriatus*	Grass	17.0	15.2	11.9	14.5	13.5	16.8	12.9	18.9	15.2	16.7	18.1	13.9	21.5	19.1	18.9
Other grasses *Poacea* spp.	Grass	2.5	0.8	10.3	6.4	9.8	12.7	17.7	15.7	19.3	20.7	19.5	13.3	16.4	11.7	11.4
Cyperaceae *Cyperaceae* spp.	Sedges	2.0	5.0	2.0	0.8	5.8	7.3	3.7	4.0	8.0	4.7	4.4	3.7	6.6	9.4	7.5
White clover *Trifolium repens*	Legume	1.8	-	-	0.0	0.0	-	0.0	0.3	0.0	0.7	0.5	-	1.0	1.0	0.3
Other legumes *Fabaceae* spp.	Legume	0.0	3.4	1.8	10.8	1.0	1.6	1.9	1.2	3.2	6.0	5.8	6.5	9.0	4.0	6.9
Tall goldenrod *Solidago altissima*	Forbs	12.2	0.3	0.5	1.3	0.8	-	3.6	-	3.0	1.5	0.5	0.5	0.5	0.0	-
Fish mint *Houttuynia cordata*	Forbs	-	0.3	1.0	1.0	2.7	0.3	1.0	1.3	1.3	1.7	0.5	1.5	2.0	4.9	3.7
Other forbs	Forbs	15.6	6.9	8.6	22.0	11.8	8.6	26.1	22.1	20.8	22.9	19.7	27.3	26.8	19.2	18.9
Shrubs	Shrubs	7.3	5.2	2.0	3.1	3.3	2.5	0.7	1.7	1.8	3.2	3.2	4.4	3.6	3.2	2.2

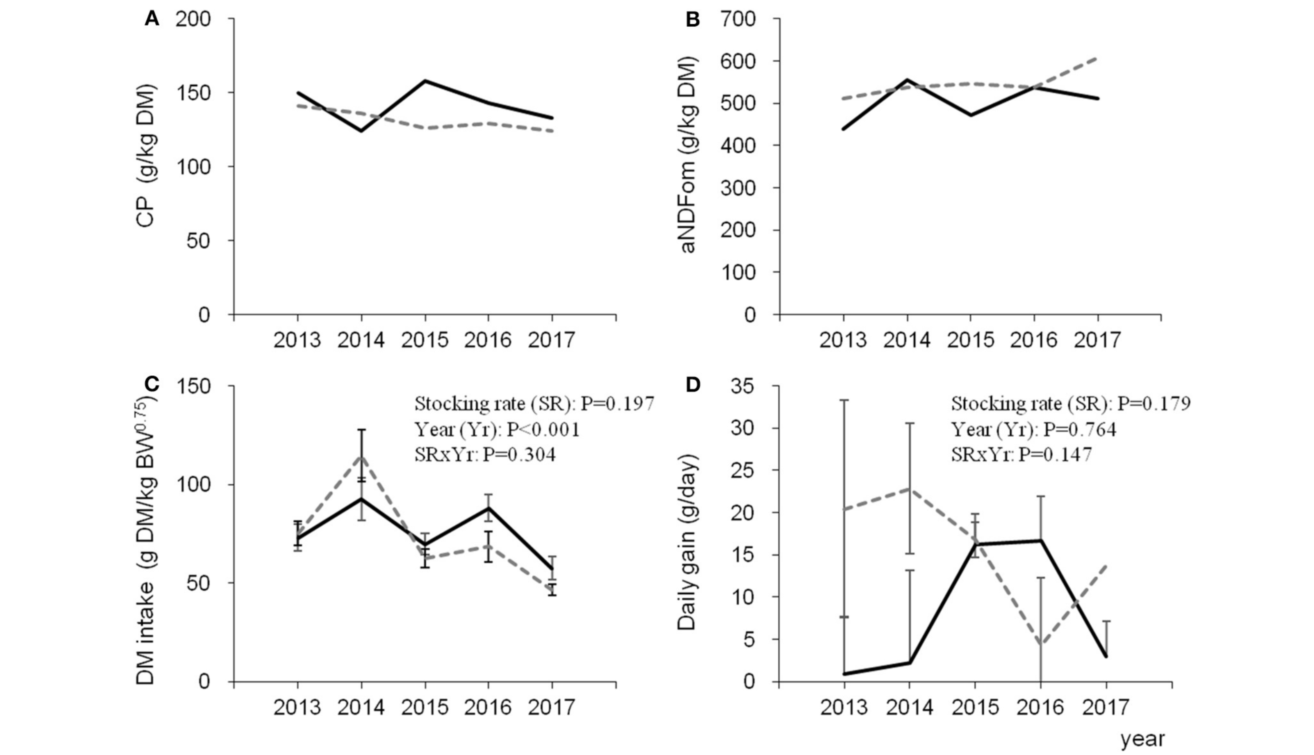

FIGURE 1 | Crude protein (CP: **A**) and neutral detergent fiber (aNDFom: **B**) contents in ingested forage, and dry matter (DM) intake **(C)** and daily gain **(D)** of grazing goats in high stocking rate (—) and low stocking rate (– – –) during five-year grazing at an abandoned field.

where, *Pc* is purchase price of a goat, *Cp* is selling price at the culling, *Wyr* is working years of a goat, *AMc* is annual management cost for a goat, *Oc* is operating cost, and *Wday* is working days per year. *Pc* was estimated according to the market price in the previous 5 years (National Livestock Breeding Center, 2018); *Cp* was estimated at 6,000 yen according to the market price; *Wyr* was assumed to be 7 years; *AMc,* including feeding cost out of the weeding period and health management, was set at 70,000 yen/yr; *Oc*, including shelter and fence, tax and public dues, and sundries was estimated at 30,000 yen/yr according to past records of a weeding contractor; and *Wday* was considered as 84 (40%), 105 (50%), and 126 (60%) days during the grazing season (210 days: from May 1st to November 30th)—and considered that the daily fee for using a goat decreases as goats become more engaged in weeding. Weeding cost per 1,000 m^2 was determined according to this goat fee and grazing/weeding days at the site.

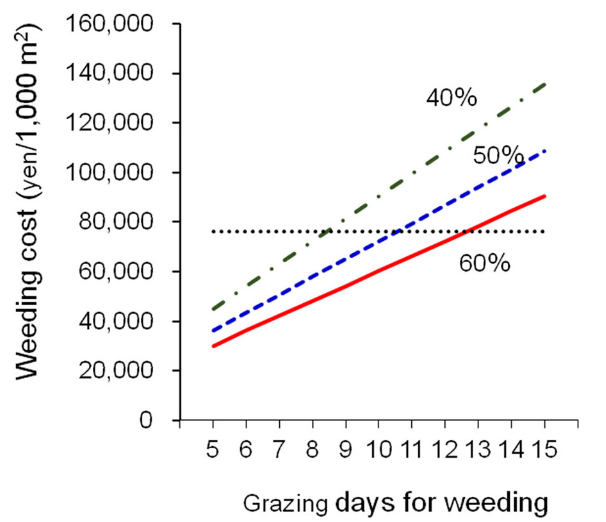

FIGURE 2 | Comparison of weeding cost by goat grazing and human mowing with a brush cutter. Cost for goat weeding at an annual operating rate (days) of 40% (84 days: -·-), 50% (105 days: - -), and 60% (126 days: —). Cost for human weeding (······).

RESULTS AND DISCUSSION

Vegetation Dynamics and Goat Performance

Goat grazing at different stocking rates did not decrease forage biomass over time, but it clearly affected botanical composition. The dominant plant species at HS changed from bamboo to tufted grass species over 5 years, while dwarf-bamboo was continuously dominant at LS (**Table 1**). Both bamboo and dwarf-bamboo are resistant to defoliation due to rhizomatous and vegetative reproductive (Fujii and Shigematsu, 2008). However, although goat grazing effectively reduced the dominance of bamboo, it did not reduce that of dwarf-bamboo.

The number of plant species increased from 33 in the 1st year to over 50 in the 5th year, regardless of the stocking rate. The Shannon diversity index also increased from the 1st to the 5th year at both stocking rates (HS: 2.3–2.8; LS: 2.1–2.6). These results suggest that goat grazing in the abandoned field for 5 years clearly changed vegetational composition, increased the number of plant species, and improved plant diversity, although stocking rate had little effect on plant diversity (Herrero-Jáuregui and Oesterheld, 2018).

Changes in botanical composition affected diet quality (**Figure 1**). At HS, diet quality—reflected by crude protein (CP) and neutral detergent fiber (NDFom)—was relatively constant throughout the study period, whereas at LS, diet quality decreased over the 5 years, leading to a decrease in forage intake by LS goats. Although goat grazing altered vegetation quality, the goats maintained their body weight and nutritional status over the 5-years period at both stocking rates (**Figure 1**). Therefore, the use of grazing for the sustainable management of abandoned fields did not negatively affect the nutritional status of goats.

Economic Potential of Goat Weeding

The daily fee for goat weeding was estimated at 1,291, 1,033, and 861 yen/goat at a 40, 50, and 60% operating rates, respectively. Imai and Nakanishi (2015) estimated a daily fee of 400–500 yen/goat based on an interview survey with several goat weeding contractors. As they did not include the initial cost of purchasing goats in their estimate, our estimate of daily fee is considered reasonable even though it is almost twice as high as their estimate.

As previously mentioned, human weeding requires 76,400 yen/1,000 m^2. The cost for goat weeding was lower than that for human weeding until 8 days/1,000 m^2 in all scenarios tested (**Figure 2**). Considering that goats remove weedy herbs in 10 days at an operating rate of 60% during the grazing season, goat weeding costs <80% of human weeding. However, the cost of using goats increased with number of days; i.e., goat weeding might not be appropriate if the weeding site includes rank growth of weedy plants and encroachment of shrubby plants. Overall, the present results suggest economic advantages of goat grazing for managing field abandonment under some conditions; however, if an abandoned field is closed by tall weedy and shrubby plants, mowing by a brush cutter or other machine should be the first approach to remove these plants. Then, goat grazing can be useful and cost effective to maintain the filed condition well.

CONCLUDING REMARKS

Intensification of agricultural processes and livestock production is effective and inevitable for economic growth. However, it also negatively affects the use of land and other resources, as well as biodiversity and the rural landscape. The present results suggest that goats grazing is useful and economical for restoring, managing, and conserving agricultural field environments, if the field does not cover rank growth and shrubby plant community. However, the present findings should be tested in different sites, because origin, management history and surrounding environment may affect the response of plant community to goat grazing.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The animal study was reviewed and approved by The Committee for Animal Research and Welfare of Gifu University. Written informed consent was obtained from the owners for the participation of their animals in this study.

AUTHOR CONTRIBUTIONS

MY and KD contributed to study conception, design, and data collection. KD performed the statistical analysis. MY simulated economic potentials and wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Managing Rangelands Without Herding? Insights From Africa and Beyond

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In many parts of the world, the utilization of rangelands is based on the targeted movement of herds within and across often vast territories. Crucial for the success of these livestock operations are decisions on how to flexibly allocate animals to the existing vegetation, both in terms of numbers and concentrations, and in space and time. Research from large scale ranching in the prairies of the Americas, and nomadic or transhumant livestock systems in Africa, the Middle East, and Central Asia, suggests that the more precisely specific patches of vegetation at a specific development stage can be targeted, the more beneficial will be the outcome in terms of animal nutrition and productivity. This also holds for the provision of environmental services such as aboveground net primary production, biodiversity preservation, and soil fertility. However, herding requires year-round labor investment, and in rural areas where seasonal migration is an important livelihood strategy, herding may suffer from absence of skilled workforce. Additional obstacles are political neglect and land use competition, insecurity, reduced self-ownership rates of herds, partial social isolation of herders, and hardship of the work. These make herding an increasingly unpopular occupation, especially for the young generation, but there are also factors that drive (young) people to take up or continue this profession. Reduced herding efforts, reflected in the reluctance to utilize remote grazing areas, may lead to overstocking of favorable pastures. This increases the risk of pasture degradation, long-term reduced herd productivity, social conflict, and public criticism of pastoralism as an anachronistic lifestyle and detrimental land stewardship, thereby further fueling the erosion of herding. By reviewing studies from Africa, the Middle East, and southern and eastern Asia, and including some insights from Europe and southern America, we discuss the ecosystem services produced by herding and herd mobility, and reflect on the ecological and social consequences of the loss of herding labor. Highlighting aspects that speak for this occupation at the individual level, we conclude by suggesting interventions that may sustain the herding profession, such as facilitation of labor sharing, labor contracts, improved herder security, and societal payments for ecological and cultural services.

Keywords: arid regions, ecosystem services, labor scarcity, knowledge erosion, marginal land, mobility, pastoralism, social isolation

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INTRODUCTION

Rangelands—which account for 40% of the global terrestrial surface (Briske and Woodward, 2016)—support human livelihoods through the grazing of herbivore livestock. Since most of the world's rangelands are located in arid and semi-arid regions, sustainably managing grazing requires a high flexibility of livestock movements, and adjustment of animal numbers and grazing duration to the spatio-temporal variability of forage resources (Bailey et al., 2019). Traditionally, this is predominantly achieved through herding livestock. Even though (virtual) fencing and supplementation strategies can also be applied (Bailey et al., 2019), they require higher monetary input and often have a lower success rate than herding. Herding is, therefore, a key strategy to sustain the multiple globally relevant ecosystem services of rangelands (Briske and Woodward, 2016), and the rationale of livestock mobility, previously viewed as a backwards feature of traditional pastoralism (Niamir-Fuller, 1999), has now been widely embraced by the international development community. Yet, at the same time as this shift in opinion occurs, members of herding families and communities themselves are increasingly seeing no future in herding as a profession. Many contemporary studies report on the decline of herding activities, herd mobility, and an erosion of pastoral livelihoods around the world (Hampshire and Randall, 1999; Niamir-Fuller and Turner, 1999; Fernández-Giménez and Lefebvre, 2006; Homewood, 2006; Hobbs et al., 2008; Galvin, 2009; Sayre et al., 2013; Turner et al., 2014).

In this contribution we elaborate on the supporting, provisioning, regulating, and cultural ecosystem services of herding sizeable flocks of mobile livestock, mostly in agro-/pastoral societies that utilize extensive communal rangelands. Yet, even on commercial ranches livestock may be herded (Bailey et al., 2019) and, where appropriate, we will also refer to this practice. We try to identify reasons for the widely observed loss of interest in livestock herding by addressing the complexity of the herding tasks and the social-ecological conditions under which they are accomplished. Thereby we partly distinguish if the herding person owns the guided flock, is an (unpaid) family member of the flock owner, or a (paid) hired laborer. Irrespective of the herder's age, position, and gender, livestock herding is difficult work that often involves social isolation and limited human nutrition during at least parts of a day (Moritz, 2008; Moritz et al., 2011; Legeard et al., 2014). It also may expose the herder to life-threatening situations such as severe weather, predating animals or banditry. Yet, herding livestock implies not only a range of constraints but also benefits, which are influenced by social and ecological conditions. Understanding these is important to anticipate how herding systems might evolve over time. Such appreciation is needed because irrevocable changes in herding systems may have important ecological, economic, and social consequences.

HERDING TASKS

According to the Oxford English Dictionary (www.oed.com), herding is defined as "Tending sheep or cattle," but this comprises of course also other herbivore species kept and managed in herds. Irrespective of the gender and cultural background of the herding person, location, season, and tended animal species, the nutrition of the flock is at the core of the daily herding tasks. This is achieved by guiding the animals across the landscape and providing them with nutritious plants, drinking water and, occasionally, mineral-rich plants or soils, while at the same time preventing field crop and tree damage and mingling of the herd with other flocks. Depending on animal species, regional and cultural settings, and season, further daily tasks include care for newborn animals, their temporal separation from the mothers, milking of lactating females, and locking up the herd in a night corral that protects from predators and thieves. Tasks of milk sale or transformation may be added during times of high milk availability. Work that occurs regularly, but not on a daily basis, includes shifting of night corrals, prophylactic health care measures such as vaccination, treatment against ecto- and endoparasites, and claw trimming. Seasonally relevant are activities related to reproduction management (selection of breeding females and males, temporal inclusion of males in the breeding herd), castration of males not used for breeding, and culling of old or infertile females and males. Once a year shearing or combing of fiber-yielding animals is required, while other tasks are contextual such as marking of new animals in the herd, animal sales and slaughter, hay making, and pen preparation for the winter time (LPV, 2007; Turner, 2009; Legeard et al., 2014; Stépanoff et al., 2017; Soma and Schlecht, 2018; Gantuya et al., 2019).

The multitude of herding tasks, and especially the core activity of guiding and supervising daily grazing, requires the active regular management of animals by a highly skilled person. While being a necessary condition for spatial movements of livestock, herding can result in variable levels of mobility (Turner and Schlecht, 2019): it is both part of sedentary systems where animals are managed around a fixed point, as well as of transhumant and nomadic systems where distance and orientation of flock movements vary according to season. In the latter systems, there is wide variation in the degree to which the locations of the animals' overnight bases change seasonally (Turner and Schlecht, 2019). Furthermore, herding labor invested into grazing management varies widely, depending in particular on the itineraries of livestock on pasture when feeding. In this respect one can distinguish three categories: (i) the "full herding mode" (further termed "herding" and in the center of our debate) whereby a person attends a flock of animals during grazing; (ii) the "herd-release mode" whereby a person guides the flock to a specific location in the morning and then leaves the animals to graze and return to their night resting place on their own or recollects them on pasture later in the day; (iii) the "unattended mode" whereby the flock, throughout its departure from the night resting place until its return to this point, remains on its own (Turner et al., 2005). Herding modes may alternate temporarily according to season, herd composition (age and sexes), and environmental as well as social contexts (Stépanoff et al., 2017).

HERDING PROVIDES MULTIPLE ECOSYSTEM SERVICES

It is not easy to elaborate on the benefits of herding in comparison to fenced or unattended grazing of an area by herbivore livestock, because several of the ecosystem services are, at a first glance, provided by any grazing system, no matter the mode of attending the animals and restricting them to the piece of land to be grazed. However, for each of the points specified below, we will elaborate the advantages of the herding duty, which we define as the judicious decision on when and how long to move a given herd to a specific pasture—on a daily, weekly or seasonal basis (Anderson et al., 2014; Lécrivain et al., 2014). Exploiting vast (semi-/arid) rangelands with spatio-temporally highly variable abiotic and biotic environmental conditions, by mobile flocks of herbivorous animals, has been widely reported to be ecologically adapted and economically sound (Butt, 2010; Behnke et al., 2011; Brottem et al., 2014; Turner et al., 2016a). At the level of the individual animal and the herd, skillful herders move the animals across the landscape to best meet their nutritional requirements, which vary across seasons and individuals as well as during a day (Van Soest, 1994). Skillful herding aims at offering the animals the most nutritious forage possible (Turner and Hiernaux, 2008; Butt, 2010; Lécrivain et al., 2014), and a higher amount of biomass than under unattended grazing (Turner et al., 2005) or random walks (Schlecht et al., 2006). Accordingly, well-nourished animals will show good performance with respect to growth, reproduction, lactation, and health (Krätli et al., 2013). This benefits their (employed) herders and owners, as well as the customers of live animals and the consumers of meat and milk. Herding can, therefore, improve the provisioning services of any of the pastoral systems defined by FAO (2001). By-products that are not easily altered in their quantity and quality by the herding mode are hides/skins and horns. For fiber provided by sheep, goats, camels, camelids or yaks, it is especially the cleanliness of the material that may improve with herding. While adequate animal nutrition stabilizes fiber yield, it cannot substantially enhance this genetically determined trait once the supply of sulfur-containing (essential) amino acids or their precursors is granted (Van Soest, 1994).

Herding the animals during nighttime instead of daytime provides additional grazing opportunity during hot parts of the year, which often coincide with periods of feed scarcity and poor feed quality (Turner and Schlecht, 2019). Since animals may increase their resting periods during the noon hours, usually the hottest part of the day, feed intake and animals' condition improve through night grazing (Turner and Hiernaux, 2008). Even though unattended animals may also night-graze on their own, the time they are actively feeding during the night is shorter and often restricted to the neighborhood of their corral as compared to herded night grazing (Ayantunde et al., 2000a,b). Within a fenced paddock, night grazing of unattended animals may be safe, whereas predators and physical obstacles may threaten the well-being of animals grazing in open areas (Scotton and Crestani, 2019). Furthermore, in areas where animal theft is common, herded animals are better protected. Yet, where armed robbery and terrorism prevail, herders practicing night grazing may even face higher risk of being attacked than during the day when the pastures are more populated (Ayantunde et al., 2000b).

As far as the provision of livestock dung is concerned, and its use as fertilizer, composting substrate, building material or fuel, herding can enhance its use-efficiency by concentrating excreta on specific fields through night-corralling. In the Sahelian and Sudano-Sahelian zone, but also in mountainous regions of Europe, this was traditionally promoted through manuring contracts (Heasley and Delehanty, 1996; LPV, 2007). Manure can also be accumulated in night corrals from where it can be collected and utilized for different purposes. Quantity and quality of excreta deposited on corralled fields, and in (night) resting areas, are primarily determined by those herding skills that govern quality of forage encountered and quantitative feed intake (Schlecht et al., 2004; Ayantunde et al., 2018). Manure quality, especially its concentration of undigested—fibrous—plant material and of phenolic compounds such as tannins, determines the rate and extent of decomposition by soil microbiota (Somda and Powell, 1998; Ingold et al., 2018), thus affecting supporting ecosystem services. The choice of the herds' resting place, and time spent there, determine the amount of excreta deposited but do not alter manure quality. Targeting excreta on specific fields or accumulation spots is not easily accomplished with unattended animals that are grazing fenced paddocks. Commercial ranches in Kenya often use makeshift enclosures to corral livestock at night with the objective of targeted dung concentration to generate areas of highly nutritious vegetation. Mixed livestock-wildlife operations may employ this system to create areas of attraction for herbivore wildlife for purposes of touristic game viewing (Porensky and Veblen, 2015).

In adjusting animal numbers and grazing duration (stocking densities), as well as re-/visits to vegetation composition, phenological stage, biomass yield, and soil conditions of a pasture, herding also provides a series of supporting as well as regulating services. Firstly, it can maintain or enhance aboveground net primary production and with it root growth of herbaceous species (Kurtz et al., 2016). Well-fed and thus well-performing animals emit less carbon dioxide equivalents per unit of milk or meat produced than less well-fed animals. Therefore, herding can contribute to decreasing the carbon footprint of pastoral systems by lowering carbon emissions per unit of produce and by increasing pasture-based carbon sequestration (Kurtz et al., 2016; Vigan et al., 2017; Stanley et al., 2018). On the other hand, also removal of herbaceous biomass and keeping landscapes open is a service provided by herders and their flocks. In Europe, for example, various culturally very old and unique landscapes, with specific structure and biodiversity such as the Lüneburg Heath or the Swabian Jura, depend on transhumant herding systems (Härdtle et al., 2002). In the Mediterranean regions of France and Greece, keeping understory vegetation short by herded flocks of small ruminants is an important service to prevent or at least decrease the risk of summer bush fires (Legeard et al., 2014; Rodríguez-Ortega et al., 2014).

Trampling, especially by small ruminants, may compact sandy soils and thus decrease erosion risk, as demonstrated by the traditional dike sheep farming along the coastal zone of the

North Sea in The Netherlands and Germany (van Bodegom and Price, 2015). If herds are specifically guided to silty loams immediately before the onset of the rainy season in tropical regions, trampling can also loosen soil crusts, and by this enable plant re-colonialization of spots sealed with micro-crusts (Hiernaux et al., 2009). Yet, loosening soil crusts in the dry season, when recolonization will not immediately follow, may lead to wind and eventually also water erosion of the loosened topsoil (Belnap, 1995). Thus, soil fertility management through grazing animals must identify the exact timing of hoof action with respect to soil and climatic conditions (Savadogo et al., 2007). Furthermore, skillful herding can make use of the animals' function as vectors that redistribute nutrients and organic matter within and across landscapes (Schlecht et al., 2004, Turner and Hiernaux, 2015).

By using locally adapted herbivores, traditional herding often contributes much more than paddock-based grazing operations to maintaining the genepool of critically endangered livestock breeds with their unique adaptive traits to hot or cold climates, poor feed quality, mountainous terrain, and specific disease challenge (LPV, 2007; Köhler-Rollefson et al., 2009; Kaufmann et al., 2016). Whereas, Fulani in West Africa, Maasai in East Africa, and herders in Madagascar, Oman, and eastern and southern Asia conduct their herds on foot with a variety of whistles and herding stick signals, herders in Central Asia, the Americas, and Oceania often move their flocks from horseback. In Europe, Oceania, and North America, use of herding dogs is common (Faye, 2008). These companion animals often also belong to specific breeds with unique traits and globally shrinking purebred populations.

Last, but by no means least, herders and their herds provide cultural services, from the simple picturesque motif for tourists, coffee table books, travel guides and other media, to the preservation of century-old traditions with internationally (United Nations) recognized heritage value such as the Hunting Eagle Festival of Kazakh herders, and the "*naadal*" festivals of Mongolians. Other examples are the annual crossing of thousands of cattle into the Inner Delta of the Niger River at Diafarabé in Mali, regionally important events such as the start of the "*Cure Salée*" season for cattle herds in In-Gall, Niger, the various "*Schäferlauf*" festivals in the German county of Baden-Württemberg, and the many regional gatherings for the "*Almabtrieb*" (French: "*Désalpes*") of transhumant cattle and small ruminant herds in the European Alps. Further cultural services are the above-mentioned conservation of a diversity of regional livestock breeds, and the preservation of specific grazing-shaped landscapes that, beyond their ecological habitat functions, also have high recreational value at regional as well as international level (LPV, 2007; Metera et al., 2010; Provenza and Meuret, 2014).

HERDING NEEDS KNOWLEDGE, SKILLS, AND NETWORKS

The essence of herding is deciding about when to move an animal herd, of a given size and composition, to a specific pasture, how long to stay there, when to move further, and where to (Roe et al., 1998; Schareika, 2001; Krätli et al., 2013; Anderson et al., 2014; Savini et al., 2014). Thereby, the herder must have a good knowledge of the (different) animals' physiological status and respective nutritional requirements, their feed preferences, and feeding behavior (Turner and Schlecht, 2019). S/he should also know the botanical composition of the pasture, its biomass yield and nutritional value, the spatio-temporal distribution and availability of different (types of) pastures, and the plants' phenological status at the moment of grazing (Meuret et al., 1994; Bailey, 2005; Provenza et al., 2007). The latter aspects also require knowledge on pasture quality over time (historical knowledge/tradition) and in dry vs. moist years (Angassa and Beyene, 2003). Further necessary knowledge pertains to the presence or absence of medicinal and poisonous plants, location and qualities of soils with higher content of (essential) minerals, water availability and quality, soil borne and vector borne diseases such as anthrax and trypanosomiasis or Rift Valley fever, and of predators and poisonous animals such as snakes or scorpions (Angassa and Beyene, 2003; Feldt et al., 2020). With view to future re-usage of the grazing area, knowledge is also decisive on the growth behavior of both desired and unwanted range plants following a grazing event. Therefore, apart from deciding on the where and when to allocate a herd of animals to an area of pasture, a skilled herder also decides on whether to allow the herd to spread out or to concentrate on particular patches of vegetation, depending on the effects desired (Meuret and Provenza, 2015) in the animal (e.g., intake of more soluble carbohydrates when grazing plant tops vs. intake of more protein when grazing plants further down), and in the vegetation (e.g., increasing defoliation and trampling effects to suppress undesired range plants vs. stimulating tillering by light through moderate grazing). In the case of using companion animals for moving (horses, camels, dromedaries), guiding or guarding (dogs) the flocks, herding also requires knowledge, practice and experience in working with these individuals (Savalois et al., 2013). Another important task of herders is keeping animals out of cultivated zones to avoid crop damage and conflicts with crop farmers (Turner et al., 2016b; Feldt et al., 2020; Houessou et al., 2020). This can only be assured by full-day attendance of the flock (Turner and Hiernaux, 2008).

With mobile phones functioning in many remote regions where herders operate, the tasks of identifying the best available grazing grounds at any given moment and the possibilities to avoid conflicts, ranger patrols, and livestock raids have recently been simplified (Turner et al., 2014; Butt, 2015; Waters-Bayer and Bayer, 2016; Djohy et al., 2017). However, the typical herding tasks remain, namely to move the animals to often remote grazing grounds, to stay there for a period of a few days to several months, and to care for the herd in a setting of poor infrastructure and limited human support (Moritz, 2008; Moritz et al., 2011; Legeard et al., 2014). Shifting to unattended grazing in such situations reduces herd mobility and increases grazing pressure on areas close to campsites or settlements (Turner et al., 2005; Altmann et al., 2018); furthermore, it may increase livestock loss through predation or theft (Meriggi and Lovari, 1996; Sangay and Vernes, 2008). Yet, herding strategies may well vary for different livestock species: in some valleys of Gilgit-Baltistan (northern Pakistan), where the herd-release mode prevails for yaks, these are oriented toward a particular pasture and then left to graze on their own, and for the rest of the day the herder accompanies small ruminants. Here, the herding of small ruminants has increased the proportion of heavily stocked areas near campsites and settlements since they are guided to pasture only after the large ruminants have been released and are brought back early to the corral. This restricts grazing time and spatial range of small ruminants (Hameed et al., submitted), whereas yaks have ample time to distribute across the pastures (Khan et al., 2013).

Although herd movements and herding patterns are primarily shaped by environmental and climatic conditions, cultural and social factors, as well as institutions, often also play an important role (UNDP, 2003; Kreutzmann, 2004; LPV, 2007; Turner et al., 2014). For wider-scaled mobility patterns facilitated by herding, it is important to recognize that the locations of seasonal overnight bases are strongly affected by herders' social networks. This reflects the vulnerability of herders on the move who are managers of significant wealth "in the bush" that attracts not only wildlife predators but also thieves (Feldt and Schlecht, 2016). Having a sedentary "host" who can potentially support the bypassing herder and herd is an important consideration in choosing movement destinations. In the West African Sahel, transhumant herders often choose locations with access to markets, that are relatively secure, and where agricultural land-use pressure is sufficiently low to avoid problems of crop damage (Turner et al., 2014). While the biophysical conditions (i.e., forage, water, absence of diseases) are key, social and institutional factors are influencing broader patterns of herd mobility. For (transhumant) herders with no or only little experience in long distance movements, the knowledge exchange with experienced herders or settled agro-pastoralists is particularly important to gain spatial knowledge, build social contacts and learn how to adjust herd composition and movements to the areas visited (Bassett and Turner, 2007; Houessou et al., 2020).

For the individual or group responsible for the herd, the quantity and quality of available herding labor matters. Full herding requires following a herd for most of the day, depending on the quality of feed and the nutritional status of the livestock (Turner and Schlecht, 2019). Moreover, as outlined above, herding involves a range of activities beyond steering animals across a heterogeneously foddered landscape. Herders often perform veterinary care, scout new pasture areas, search for lost animals, transfer animals to other management herds and markets, and milk and water animals (**Figure 1**). In many dryland areas, watering animals involves the onerous task of drawing water from deep wells or digging temporary wells in dry wadi or depression areas. Moreover, the length of a grazing day increases as quality forage becomes more sparse. Herding is then more difficult and may require additional labor to navigate herds through areas of higher cultivation pressure or difficult terrain where livestock can get lost. Furthermore, herds on the move, distant from a home base, often require a minimum of two herders, so that when livestock are lost or stolen one herder can search while the other one stays with the herd (Turner and Hiernaux, 2008).

FIGURE 1 | Herders' duties requiring collaborative work: **(A)** fetching water for cattle (Niger); **(B)** shearing sheep (Mongolia); and **(C)** marketing animals (Niger).

Next to the number of available herders, the quality of their labor also matters. Herding is a profession that requires stamina, perseverance, knowledge, and the capacity to endure partial social isolation (Moritz et al., 2011). Within traditional pastoral communities, the variation in these qualities across herders is well-known (Turner, 1999; Stépanoff et al., 2017). Some of these qualities are tied to experience and ultimately age. Older herders with less stamina and strength will often be more inclined to rely on herd-release forms of grazing management, whereas youth charged with herding may display less endurance and knowledge. On the other hand, tasks may also be split between family or community members (Schlecht et al., 2009). While elders with much experience give the general direction on which areas to graze and which water points to use, younger family members will actually do the more arduous tending to the animals on pasture. In this context children are often assigned the tasks of tending to small ruminants or calves near the overnight enclosure (Turner, 2009; Aufderheide et al., 2013). Depending on the animals' physiological status, Rendille pastoralists of northern Kenya split their camels into a highly mobile "fora"-herd tended by young men of the warrior age and a less mobile "moro"-herd (Kaufmann, 1998; Aloo et al., 2008) kept closer to the homestead. While the latter flock returns to the homestead every night and supplies the household with milk, the former is often absent for long periods of time without returning to the settlement.

In different agro-/pastoral systems, the group that is responsible for assigning livestock herders varies. While the family (variously defined) is most often the herd managing unit, herds may also be managed jointly by multiple families or village communities on a permanent or seasonal basis. Joint herding can take different forms including the sharing of herding tasks by several persons, the hiring of herding labor for livestock owned by communities, the entrustment of livestock to others, and the joint movement of individual family herds together (Davies and Hatfield, 2007; LPV, 2007; Turner and Hiernaux, 2008; Li and Huntsinger, 2011; Butt, 2015). Group management may allow to access broader social networks that can be solicited during long-distance movements. Moreover, groups benefit from a broader knowledge base and greater access to herding labor. Still, the major constraint to joint management and labor sharing is that different members may have different ideas about which decisions to take when. This reflects the highly variable biophysical and social conditions under which herding operates and may even be found among brothers for family herds. Thus, labor sharing and joint herding may occur in an *ad hoc* manner or on a more temporary basis: transhumance herds move together and share labor *en route,* or herds are combined or split during the year depending on labor demands (Turner and Hiernaux, 2008).

Labor sharing often occurs during periods of particularly high labor demand. Beyond appropriate time allocation to different tasks that are directly connected to the daily herding duty, herders need support by family, peers or kin groups for laborious tasks such as disease (prevention) treatments, marking and milking the animals, hay making, and shearing (**Figure 1**). The time herders spend with their animals, and preference for individual or group herding, thus also depends on the location of the pasture and the season, as well as on tasks at seasonal campsites, on hay-making plots or at the main settlement where crop farming may take place (Sangay and Vernes, 2008; Nkedianye et al., 2011; Soma and Schlecht, 2018). As shown by the example of the Mongolian Altai, shearing of sheep, felting of wool, and vaccination of livestock are jointly organized by several families on the summer pastures. Often, it is the male household head and the older generation who are joining forces, whereas women and younger family members move to urban centers for education and employment (Fernández-Giménez et al., 2017) and only briefly visit the alpine meadows during summer vacations.

HERDING IS UNDER THREAT

High variability of precipitation has always determined forage availability in semi-/arid lands primarily exploited by herded flocks, but the effects of the recently accelerating phenomena of climate change increase the spatio-temporal variability of precipitation (Al-Kalbani et al., 2015; Lv et al., 2018). Climate change induced variation in precipitation make the adjustment of animal numbers to forage and water resources more difficult (Godde et al., 2019). In the Karakoram Mountains of Central Asia, increasingly hotter summer temperatures have been reported to lead to massive melting of glaciers (Anwar and Iqbal, 2018). Meltwater streams can wash away pathways and bridges, temporarily obstructing access to high altitude summer pastures. This was witnessed, for example, in Shimshal, Gilgit-Baltistan, in July 2017 (Hameed et al., submitted). Whereas increasing environmental variability requires higher flexibility of herd movements (Niamir-Fuller and Turner, 1999; Kreutzmann, 2011), the latter are increasingly hampered by mining activities, land development projects, and cropland encroachment onto tracking routes and pastures (LPV, 2007; Hobbs et al., 2008; Dureau and Bonnefond, 2014; Turner et al., 2014, 2016b; Haller et al., 2016). Cropland encroachment is partly triggered by population growth, but the opening up of new markets through improved infrastructure is another driver for herders' dwindling space for maneuver. It promotes the expansion of cash crop cultivation (Hobbs et al., 2008; Sayre et al., 2013; Turner et al., 2014, 2016a), and renders livestock herding more difficult at the local level. In West Africa, increasing local cropping pressures foster herd movements from the home territory during the cropping season. As cropping pressures continue to grow, households may reduce their livestock holdings and rely increasingly on stall-fed modes of management (Turner et al., 2014). In most semi-/arid regions of the world, cropping densities are highly heterogeneous and adequate pastures are only available if livestock can be moved at subnational to district scales. The ability to move despite locally high levels of competing land uses, such as agriculture, can only be maintained through government protection of key pastoral resources, such as movement corridors and water points, that allow herders to reach these pasture areas (Turner et al., 2016b). The historic neglect of pastoralists' rights to such key resources that are necessary for mobility has contributed to the erosion of both, the net benefits of herder-facilitated mobility and, as a consequence, the engagement in herding *per se* (LPV, 2007).

Another growing threat to herding is the expansion of banditry and terrorism in numerous remote arid areas of sub-Saharan Africa—from Mali across Burkina Faso, Niger and northern Nigeria into Chad, in the Horn of Africa and in arid parts of Kenya. Also affected are the more humid but sparsely settled northern zones of Ivory Coast, Cameroon, the Central African Republic (Alemu, 2018; Abdullahi, 2019; Feldt et al., 2020), and southern Madagascar (Feldt and Schlecht, 2016). Given the wealth on the hoof they are managing in highly unsecure areas, herders are at serious risk of attack. Threats of animal theft and to personal life increasingly reduce herders' safe operational space in such areas, and may even lead to abandonment of agro-/pastoral use. In consequence, land use pressure may increase in secure areas that are already more densely populated and present little opportunity for flexible herd mobility (Feldt et al., 2020).

A further reason for the erosion of herding services is the reduced labor availability for grazing management of livestock in open rangeland conditions. Shortage of herding labor may not simply be a result of household demography (e.g., a household's dependency ratio) but may result also from necessary labor diversion to other purposes (e.g., agriculture, trade). Whereas Samburu herder-owners of cattle and small ruminants in Marsabit County, Kenya, were found to start milking at 5:30 to 6:00 a.m., then taking their animals to pasture and returning to the overnight enclosure at 4:00 p.m., well-paid hired herders on a Kenyan ranch started their duties at 5:30 a.m. and returned to the enclosure at 6:00 p.m. (Aufderheide et al., 2013).

Households' decisions to invest scarce labor resources into herding are also shaped by the perceived benefits of this investment. Hereby it is important to recognize that the size of benefits from herding investments depends on the size of the herd and the degree to which the herd manager owns livestock within this herd. As herd size declines, benefits from labor investments into herding will also decline unless labor-sharing arrangements are put in place (Little, 1985; Turner, 1999). In many parts of the world, the family or individual in charge of herding may own very few animals in the managed herd, with herding services being compensated through wage or entrustment contacts (Little, 1985; Turner, 1999; LPV, 2007; Legeard et al., 2014). Due to either lower incentives for contracted herders or constraints placed on them by livestock owners, herds with low self-ownership rates have been reported to receive lower quality herding and exhibit more constricted patterns of grazing (Little, 1985; Turner, 1999; Turner and Hiernaux, 2008). However, there are also examples of high quality herding labor invested by wage-earning herders (Moritz et al., 2011; Baumont, 2014).

Loss of herding labor, whether permanent or temporary, leads to the transfer of herding tasks to elderly persons, (younger) males and females (Turner and Hiernaux, 2008), or hired local (West Africa) or foreign (Oman) laborers (De Bel-Air, 2015), as depicted in **Figure 2**; this is frequently accompanied by a decline in livestock mobility (Turner et al., 2005). If grazing the animals is assigned to less experienced persons, they often do not allocate sufficient time to herding duties and lack the aforementioned knowledge and skills (Turner and Hiernaux, 2008; Derville and Bonnemaire, 2010; Jasra et al., 2016): In Gilgit-Baltistan, young and inexperienced herders were accused of guiding the flocks rather arbitrarily and being unable to bring back all animals to the night resting place at the end of the day (Hameed et al., submitted). Declining availability of herding labor can also reduce the prevalence of longer-distance herd movements and shift grazing management toward less labor-intensive options such as the herd-release mode (Turner and Hiernaux, 2008) or fenced grazing (LPV, 2007; Legeard et al., 2014).

A

B

FIGURE 2 | Goats in the Wadi Muaydin watershed in Oman, herded **(A)** by an old Omani herder in 2009 and **(B)** by a young laborer from Bangladesh in 2018.

APPEAL OF HERDING FOR YOUTH

The erosion of the herding profession is not only shaped by reduced investments into herding by livestock owners and managers, but also by a loss of the attractiveness of herding as an occupation. Often, long hours have to be spent in remote areas with few amenities and poor communication infrastructure (Baumont, 2014; Legeard et al., 2014; Djohy et al., 2017), on a profession that the broader society depicts as primitive (Fernández-Giménez and Estaque, 2012; Feldt and Provost, 2018). Coupled with the continuous vigilance required and risks to be endured in areas of increasing farmer-herder conflicts and armed insurgencies, this decreases the profession's appeal to young men who constitute the vast majority of herders.

Herding families can include some of the wealthiest and of the poorest members of rural communities. Some herding families are sufficiently rich in livestock to offer adequate subsistence for the family and provide their young men with the resources needed to marry and establish herds of their own. For those owning few livestock, the herding profession is poorly remunerated (Moritz et al., 2011). In West Africa, for example, young men or boys simply herd for their fathers or older brothers and may receive little beyond the right to milk the livestock entrusted to them by their owners (Turner, 2009). Those who work for a wage earn very little and often take on the risk of paying for crop damage caused by livestock not owned by them but under their care (Bassett, 1994). Labor contracts are often not transparent with herders having little recourse against owners who refuse to pay herding fees. Distrust between owners and herders prevent reforms of the labor contract so that herders are not paid in animals as a living wage (Turner and Hiernaux, 2008). Understandably, there is a sense of hopelessness among herding youth who often see little economic future in an occupation that they are born into. However, in the context of modernization and intensification of the pastoral livestock sector (Schareika et al., 2020), it may even be advantageous if members of the younger generation choose other professions—as long as there are still qualified individuals available for the herding tasks (Yeboah and Jayne, 2018).

Resource-poor rural regions of the world, where pastoralism predominates, are major source areas for intra- and international labor migration of young men (ILO, 2018). Labor emigration of youth offers both challenges (Wu et al., 2014) and benefits (McKay and Deshingkar, 2014) to rural families. Due to the year-round demands for herding labor in areas such as the Sudano-Sahelian zone of West Africa, labor emigration rates among herders have historically been lower than among farming youth, whose families primarily need their labor during the cropping season (Turner and Hiernaux, 2008). Increasing migration by (young) herders often leads to schism within the family given the hardship such departure imposes on the remaining family members (Hampshire and Randall, 1999; Turner and Hiernaux, 2008; Feldt and Schlecht, 2016), and can result in herders never returning to their occupation.

Multiple and amplified challenges to herding, and the growing ambivalence about herding as a profession among rural youth, have led to a significant decline of livestock herding in many parts of the world (LPV, 2007; Kreutzmann, 2011; Fernández-Giménez and Estaque, 2012; Fernández-Giménez et al., 2017; Schareika et al., 2020). The basic conditions that have allowed herding to function effectively have faded in many regions that formerly were characterized by mobile pastoralism: unrestricted movements across vast territories, personal security, sufficient livestock ownership among herding families, remunerative markets for livestock and products, economic viability of herding contracts, working relations among herders, herd patriarchs, and owners, and social coherence within kin groups (LPV, 2007; Hobbs et al., 2008; Turner and Hiernaux, 2008; Fernández-Giménez and Estaque, 2012; Sayre et al., 2013). In some regions, the ongoing social-ecological transformations have undermined the viability of the herding profession. In other regions, herding continues despite severe challenges, due in large part to the ecological and productive benefits it provides. The "herding socialization" of children often shapes their personalities, and the everyday inclusion into herding tasks from a young age fosters the development of a pastoral personality. Many young(er) herders are aware of family or clan traditions and perceive the herd as the family's economic and social wealth (Schareika et al., 2020). They are proud of their knowledge and skills which manifest themselves in well-fed animals that are constantly compared to the herds of peers. Across different regions, strong individual commitment to the herding lifestyle can, therefore, still be found, as it provides purpose, contentment, pride, and social integration (LPV, 2007; Moritz et al., 2011; Legeard et al., 2014; Turner et al., 2014). Beyond restricted economic alternatives that may keep herders within their occupation (Adriansen, 2008; Turner, 2009), gradually acquiring their own animals may still be an option for young herders to become economically independent (Moritz et al., 2011; Gonin and Gautier, 2015). Also, in the "western" world, young women and men from urban contexts may decide to take up the herding profession because they find satisfaction in a meaningful, ecologically compatible, and valuable activity that requires and fosters a very particular relationship to the animals and the landscape and provides personal pleasure (Baumont, 2014; Legeard et al., 2014).

HERDING MERITS SUPPORT

Wherever the herding profession disappears, its multiple benefits also vanish. The above discussion of the advantages of herded grazing shows that its erosion may entail, among other things, overgrazing (Altmann et al., 2018), biodiversity loss, soil fertility decline, and in some parts of the world even increased risk of bush fires (Mancilla-Leytón et al., 2013). The judicious utilization of animal impact on vegetation and landscape in order to influence their development as a whole is one of the objectives of the more recently discussed grazing strategies (Holistic Planned Grazing—Savory and Butterfield, 1999; Targeted Grazing—Frost et al., 2012; Multi-Paddock Grazing—Teague et al., 2013; Circuit Grazing—Gregorini et al., 2017). One major tool to achieve animal impact on vegetation is concentrating large numbers of animals on defined and spatially limited areas of vegetation for a time-span long enough to achieve the desired impact by defoliation (feeding), trampling, and deposition of feces and urine. This concentration can be achieved by either narrowing the allotted pasture space for a given number of animals or by increasing the number of animals on a given space for the period of time until the desired effect is reached. The former can be achieved by dividing the available area into many small paddocks so as to achieve the stocking density needed to produce the desired effect, and then rotate to the next paddock. This is possible where enough capital is available for fencing, and where water and mineral resources can be provided easily in every paddock. In many extensive grazing systems, however, fencing is not feasible at all and water and mineral resources are distributed unevenly (Legeard et al., 2014). Yet, even in most fenced systems, paddock sizes are so large that the existing herds are far too small to achieve the desired impact. In such circumstances, pooling herds into larger grazing mobs and herding these in a "strip-grazing" mode through existing paddocks is an option to employ livestock for shaping the environment. Strip grazing is commonly used in North American grazing systems to create firebreaks (Taylor, 2006), virtually eradicating all plant matter from the grazed strip. Pooling several smaller herds into a tightly bunched larger grazing mob herded jointly by several herdsmen has also been employed in Laikipia, Kenya, to remove standing dead biomass and induce fresh regrowth, to deposit dung and stimulate vegetation regrowth on bare patches, and to increase livestock performance (Odadi et al., 2019). In Corrientes, Argentina, (unattended) high intensity grazing was experimentally employed by Kurtz et al. (2016) and showed different effects depending on its timing throughout the year. In all cases, there was additional vegetation growth in autumn and the proportion of green biomass in the overall biomass increased over the following 12 months, but most prominently when high intensity grazing was performed in winter. Pooling animals on an organic Namibian livestock farm into three large (unattended) flocks and rotating them sequentially through all ranch paddocks following a grazing plan devised according to Holistic Planned Grazing principles permitted stocking rates of 45 kg livestock biomass per hectare (range 17–48). These stocking rates were well above those of neighboring farms and still permitted taking additional animals in for grazing during drought (Isele, 2014). At the same site, an on-farm experiment comparing the customary grazing regime with the increased stocking density indicated higher forage biomass production under higher stocking (Ludwig et al., 2019). However, stocking rates and densities tested were far off the high impact grazing approach of Kurtz et al. (2016) in northern Argentina. While scientists are on one hand rather critical to recommend larger scale adoption of such herding and grazing practices, they acknowledge the reported benefits and seek ways to integrate this into their range management concepts (Briske et al., 2011; Teague et al., 2013). Given the above, skillful herding may become a new livelihood option for the youth even if livestock production may be pushed onto ever more marginal rangelands in order to free space for cropping of plant-based human food. On the other hand, reluctance to utilize remote pasture areas, loss of herding labor and herding skills, and the resulting reduction of herding efforts may lead to persistently high animal numbers in socio-culturally and economically more attractive areas than those classically used for grazing (Altmann et al., 2018). In Gilgit-Baltistan, for example, two thirds of interviewed herders classified today's conditions of alpine spring and summer pastures as poor and mentioned high animal numbers and short daily and seasonal walking distances as major reasons for the perceived degradation (Hameed et al., submitted). Much of the persistently heavy stocking was traced back to the unavailability of skilled herding labor, but also to time constrains and modern herders' aspiration for leisure. Next to (the risk of) pasture degradation, such trends reduce overall herd productivity and stimulate public criticism of pastoralism, all further fueling the erosion of (traditional) herd mobility and herding.

The difficulty of developing strategies to support the herding profession stems from the fact that its decline, as described above, is caused by a combination of different, location-specific factors. Therefore, there is no single solution, such as the formation of pastoral associations, that may effectively address the problem across regions (Fernández-Giménez and Estaque, 2012; Ulambayar et al., 2017). There are, however, a number of interventions, which, depending on local contexts, may be effective in reducing pressure on the herding profession and increase its attractiveness. Despite stereotypes of unruly movements and pastoral resistance to law and order, herding and large-scale herd mobility need a certain degree of effective governance and order to function properly (Haller et al., 2016). In agro-/pastoral areas experiencing rapidly expanding agricultural pressure, government support and on-the-ground protection of key pastoral resources is needed to enable mobility. If herd mobility is inhibited by insecurity or land use pressure, the productive benefits of herding decline relative to more labor-extensive forms of livestock rearing. Therefore, governments around the world are well-advised to pass legislations that aim at protecting pastoral resources such as movement corridors, water points, and encampment locations (Brottem, 2014; Hubert et al., 2014; Kitchell et al., 2014). Indeed, in its policy framework for pastoralism, the African Union (2013) has highlighted the need for pro-pastoral interventions, and several African countries developed policies to facilitate mobility at national and regional level (Bonnet and Hérault, 2011; Dongmo et al., 2012; AFD, 2014). What is less widespread is a consistent framework fostering local communities to develop land use agreements that accommodate herder-facilitated livestock movements to key pastoral resources at least on a seasonal basis (Kitchell et al., 2014).

Another promising approach to stimulate herding consists in the support of local mechanisms for labor sharing. These should not only include the recognition of customary forms of joint livestock management, but also increase the use and security of livestock entrustment and herding wage contracts. Livestock owners must feel secure when allowing their animals to be managed in distant pastures by someone else. In many places, more persistent and tractable ownership markings on animals will help the building of trust between herders and livestock owners. Information sharing about the locations of herds, as facilitated by mobile phone use, would help as well.

Overall, herding as a profession needs to be better remunerated with respect to alternative livelihood pursuits (LPV, 2007; Fernández-Giménez and Estaque, 2012; Legeard et al., 2014). Herding may not be abandoned because livestock rearing *per se* is not profitable, but because only a very low fraction of the profit is allocated to herding services (Aufderheide et al., 2013). Some herders reportedly state that they must steal from the owners' livestock in order to support their families given their low wages. Livestock owners, on the other hand, recognize that effective wages are low, but also emphasize that they are unwilling to compensate herders more fairly because they are stealing their livestock (Turner, 2009). Such situations require the development of institutions that secure ownership claims to livestock and develop adequate wage levels for employed herders (Aufderheide et al., 2013).

In many parts of the world, the current declines in herding as a profession are neither due to forced sedentarization and livelihood change, nor has there been a significant expansion of feedlots or ranching systems by governmental initiatives. Instead, traditionally mobile pastoralists themselves shift to such modes of livestock rearing because they currently perceive higher benefits in a world governed by "capital logic" (Schareika et al., 2020). To halt this trend, the multiple ecosystem services provided by skillful herding of domestic herbivores must be recognized and rewarded by society, not only by attributing an "intangible cultural heritage" label to herding, but by allocating tangible (financial) benefits. Furthermore, the recognition and appreciation of this profession as an ecologically important high-quality activity may also need to be assisted by professional training programs (Fernández-Giménez and Estaque, 2012; Jallet et al., 2014).

CONCLUSIONS

Being based on in-depth knowledge and judicious utilization of ecological processes rather than on external inputs, the laborious task of skillful herding greatly contributes to the sustainable utilization of pastures, particularly in the world's marginal, semi-/arid and mountainous regions. Recognizing and rewarding its multiple ecosystem services, developing mechanisms and tools that make herding less strenuous and politically, socially and financially more secure and attractive, might at last slow down the erosion of this millennia old profession and livelihood strategy and at the same time promote sustainable rangeland and landscape management.

AUTHOR CONTRIBUTIONS

ES: conceptualization and initial writing. MT: contribution on mobility, labor, and policies. CH: contribution on grazing impacts on vegetation. AB: contribution on animal-soil-plant interactions and photographs. ES, MT, CH, and AB: final shape of manuscript. All authors contributed to the article and approved the submitted version.

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REVIEW
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The Shrinking Resource Base of Pastoralism: Saami Reindeer Husbandry in a Climate of Change

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The productive performance of large ungulates in extensive pastoral grazing systems is modulated simultaneously by the effects of climate change and human intervention independent of climate change. The latter includes the expansion of private, civil and military activity and infrastructure and the erosion of land rights. We used Saami reindeer husbandry in Norway as a model in which to examine trends in, and to compare the influence of, both effects on a pastoral grazing system. Downscaled projections of mean annual temperature over the principal winter pasture area (Finnmarksvidda) closely matched empirical observations across 34 years to 2018. The area, therefore, is not only warming but seems likely to continue to do so. Warming notwithstanding, 50-year (1969–2018) records of local weather (temperature, precipitation and characteristics of the snowpack) demonstrate considerable annual and decadal variation which also seems likely to continue and alternately to amplify and to counter net warming. Warming, moreover, has both positive and negative effects on ecosystem services that influence reindeer. The effects of climate change on reindeer pastoralism are evidently neither temporally nor spatially uniform, nor indeed is the role of climate change as a driver of change in pastoralism even clear. The effects of human intervention on the system, by contrast, are clear and largely negative. Gradual liberalization of grazing rights from the 18th Century has been countered by extensive loss of reindeer pasture. Access to ~50% of traditional winter pasture was lost in the 19th Century owing to the closure of international borders to the passage of herders and their reindeer. Subsequent to this the area of undisturbed pasture within Norway has decreased by 71%. Loss of pasture due to piecemeal development of infrastructure and to administrative encroachment that erodes herders' freedom of action on the land that remains to them, are the principal threats to reindeer husbandry in Norway today. These tangible effects far exceed the putative effects of current climate change on the system. The situation confronting Saami reindeer pastoralism is not unique: loss of pasture and administrative, economic, legal and social constraints bedevil extensive pastoral grazing systems across the globe.

Keywords: Arctic, climate change, encroachment, grazing rights, infrastructure, pastoralism, reindeer, Saami

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INTRODUCTION

The productive performance of free-living large ungulates, including wild populations and domestic herds managed in extensive pastoral grazing systems, is modulated by two kinds of drivers: those associated with variation in the natural environment and those associated with human intervention independent of the natural environment (Godde et al., 2018). These act simultaneously and together constitute the holistic climate of change that governs the performance of animals and hence the well-being of people—in particular pastoralists—whose livelihoods depend on them. The two kinds are nevertheless commonly considered separately: environmental interactions are principally modelled and reported in ecological literature while the influence of socio-economic and other anthropogenic developments is explored mainly in anthropological and geographical literature. The disciplinary divide sharpens the focus of analyses but constrains interpretation of their results. The growth and performance of large ungulates, and the dynamics of the (socio-)ecological systems of which they are a part, obviously reflect the integrated effect of all the drivers that impinge on them, not just those of one particular kind. The partial effect of drivers of one kind likewise necessarily depends on the partial effect of those of the other but this relationship, too, is lost across the disciplinary divide. In this paper we use Saami reindeer husbandry in Norway as a model in which to examine how environmental variation and human intervention impinge jointly on a pastoral grazing system and from which to assess the relative impact of each on such a system. Several of the drivers we examine are specific in their character or their settings to the boreal region and even particular to Saami reindeer husbandry in Norway: our approach, however, is entirely general in its application and our conclusion reflects the situation in many, perhaps even most, extensive pastoral grazing systems.

Ecological studies of the dynamics of extensive grazing systems are primarily concerned with the influence of natural variation in conditions and resources on the performance of animals or on the ecosystem processes that modulate it. 'Conditions' in this respect include abiotic factors that influence organisms such as temperature, precipitation, wind, photoperiod and, for chionophile organisms like reindeer/caribou (*Rangifer tarandus*; **Box 1**), the characteristics of the snowpack. Conditions also include biotic components such as the density of conspecifics, competitors, predators and parasites. Resources are things required by and also reduced by the activity of organisms (or by the activity of other organisms): food, shelter and mates are examples (Begon et al., 2006). World attention is currently directed increasingly and often passionately toward the effects of climate variation on conditions, on levels of resources and hence on the performance of animals and the function of the ecosystems of which they are a part. Climate effects include the degradation of grazing lands though desertification, encroachment of bush and woodland and deforestation (Asner et al., 2004), the modulation of the phenology, growth and the nutritional quality of herbage (Herrero et al., 2016; Thackeray et al., 2016), the modulation of the phenology, growth and patterns of migration of animals (Forchhammer et al., 1998; Ozgul et al., 2009; Robinson et al., 2009; Sheridan and Bickford, 2011; Thackeray et al., 2016) and, arising from these, the modulation of the dynamics of animal populations (Coulson et al., 2001; Post and Forchhammer, 2002; Post et al., 2009a; Marshal et al., 2011; see also IPCC, 2019).

Effects of human intervention on the abundance and performance of free-living large ungulates are readily apparent, often negative and not infrequently dramatic. Unrestrained hunting for meat, hides and bone in the latter half of the 19th Century, for instance, reduced bison (*Bison bison*) in North America from around 60 million to some few dozen animals and deer (*Odocoileus* spp.) from 50 million to some few thousands (Soper, 1941; Isenberg, 2000; VerCauteren, 2003; Webb, 2018). At the same time saiga antelope (*Saiga tatarica tatarica*) in Central Asia were driven, it is thought, to the verge of extinction by hunting for meat, hides and horns (Bekenov et al., 1998; Milner–Gulland et al., 2001). An estimated half million Canadian barren-ground caribou (*R. t. groenlandicus*) were killed by hunters between 1949 and 1954 (Kelsall, 1968, p. 201) and, in the following two decades, half a million wildebeest (*Connochaetes taurinus*), deemed a threat to domestic cattle in Botswana, died in extermination programmes and as a result of the construction of veterinary cordon fences which excluded the animals from dry season access to water (Williamson and Williamson, 1984; Spinage, 1992; Gadd, 2012). These instances, directly or indirectly, were deliberate acts of destruction. By contrast, the introduction of the rinderpest virus (*Rinderpest morbillivirus*) from Arabia or India in 1889, which led to devastation of buffalo (*Syncercus caffer*), wildebeest and the death of around five million cattle in Southern and East Africa, was presumably an accident, albeit one on a monumental scale (Sinclair, 1977; Phoofolo, 1993; Van den Bossche et al., 2010). Examples of positive effects of human intervention on large ungulate grazing systems include the maintenance (as opposed to the deterioration) of the conservation status of many species of ungulates worldwide (Hoffmann et al., 2015; Barnes et al., 2016), the enhancement of primary and secondary production through grazing management (Odadi et al., 2017; Crawford et al., 2019; McDonald et al., 2019), and the successful—at least in numerical terms—introduction of species such as horse (*Equus caballus*) to North America (current population 9 million; McKnight, 1959; American Horse Council Foundation, 2018) and sheep (*Ovis aries*) to Australia (current population 93 million; FAO, 2019).

Reindeer pastoralism, practiced across some 10 million km^2 of northern Eurasia, constitutes the largest contiguous ungulate grazing system on Earth (**Box 1**). The performance of these animals and this system is influenced by both effects, i.e., by variation in the natural environment and, the remoteness of the system notwithstanding, also by human intervention. Considering the former, the mean annual temperature of the Arctic has increased by about 2°C since 1960 (**Figure 2**). This is more than twice the mean global increase and considerable attention has been directed toward examining the effect of this on the species, the ecosystems and the peoples of the North (ACIA, 2005; Overland et al., 2017; Post et al., 2019). Not surprisingly, large scale warming influences the tundra,

BOX 1 | Reindeer and the northern grazing system

Reindeer, *Rangifer tarandus*, is a boreal to super-boreal species complex within the monospecific genus *Rangifer* (family *Cervidae* [deer]). The species has a circumpolar boreal (Arctic and sub-Arctic) distribution. The animals are called—in English—'caribou' in North America and 'reindeer' in Eurasia. Distinction is also generally made between wild and domesticated reindeer, the latter being herded by indigenous peoples (**Figure 1**). The term 'semi-domesticated' is frequently applied to herded reindeer (e.g., Colman et al., 2013; Meng et al., 2014; Uboni et al., 2016) but the prefix is superfluous. The distinction between 'domestic' and 'domesticated' animals is clear, comprehensive and sufficient (see Clutton-Brock, 1987, p. 104). All three forms (caribou, wild and domesticated reindeer), of course, are the same species (Flagstad and Røed, 2003; Røed et al., 2008, 2011). There are ∼5–6 million *Rangifer* worldwide, including 3–4 million caribou and wild reindeer and ∼2.5 million domesticated reindeer of which 650,000 are in Fennoscandia (CAFF, 2013; Gunn, 2016; Government of Norway, 2017; Norwegian Agriculture Agency, 2019a).

FIGURE 1 | Some 24 indigenous peoples graze some 2.5 million reindeer (*Rangifer tarandus*) across 10 million km^2 of mountain, forest, taiga and tundra in northern Eurasia. This is an area equivalent to 7% of the land surface of the globe.

Rangifer belong to the intermediate feeder type (Hoffman, 1989). The animals select a species rich diet of browse and non-woody plants, and unusually for ruminants, they may take a considerable amount of lichens (especially, but not exclusively, in winter; Trudell and White, 1981; Boertje, 1984; Adamczewski et al., 1988; Mathiesen et al., 2000; Sundset et al., 2010). Their supply of forage is highly seasonal. In the boreal zone plant growth is restricted to the period from late May to early September when the daily mean ambient temperature is >0°C: for the rest of the year plants are frozen and therefore inert. The animals therefore normally have access to fresh green forage only for 3–4 months annually when, during the boreal summer, they grow, fatten and rear their young. In winter, by contrast, the available biomass of green material is reduced because plants enter dormancy and access to them is restricted by snow. *Rangifer* display a suite of adaptations to this situation, the most conspicuous being migration between spatially distinct summer and winter pastures.

Barren-ground caribou in northern North America and wild reindeer in Siberia migrate north in spring to tundra pastures around the rim of the Arctic Ocean. Here they spend the summer before returning hundreds of kilometers south in autumn to winter pastures in the taiga and boreal forest inland (Kelsall, 1968; Parker, 1972; Chernov, 1985; Fancy et al., 1989). Northwards migration in spring is in part a response to the progressive emergence of fresh herbage which appears at the edge of the retreating snowline. This has been likened to a 'green wave' which the animals track as it spreads northwards across the landscape (Skogland, 1984, 1989; see also Aikens et al., 2017; Middleton et al., 2018). *Rangifer* trade quantity for quality, the small size of new shoots being compensated by their high nitrogen content and digestibility (Russell et al., 1993; Van der Wal et al., 2000; Johnstone et al., 2002).

Feeding conditions in winter when plants are inert are influenced by the quality of the snowpack. Wind, and in some areas, recurring cycles of thawing and re-freezing associated with interludes of mild weather sometimes accompanied by rain, increases the density and the hardness of snow consequently making it difficult for the animals to dig down to reach the plants beneath (Schnitler [*circa* 1751] in Hansen and Schmidt, 1985, p. 24; Woo et al., 1982; Bartsch et al., 2010; Tyler, 2010; Forbes et al., 2016; Langlois et al., 2017). Forests provide shelter from wind and thaw-freeze cycles are less frequent inland where the climate is generally colder and drier than at the coast where, where there is open water, it is warmer and wetter. Both factors contribute to easier snow conditions, and hence better grazing, and the animals therefore move inland to the forest zone where they spend the winter. Domesticated reindeer follow the same pattern as their wild conspecifics, resulting in the spectacular seasonal migration of herds and herders—usually hundreds and sometimes of more than 1,000 km each way—which are a prominent feature of reindeer peoples everywhere (Manker, 1935; Krupnik, 1993; Paine, 1994; Vitebsky, 2005; Dwyer and Istomin, 2009; Degteva and Nellemann, 2013).

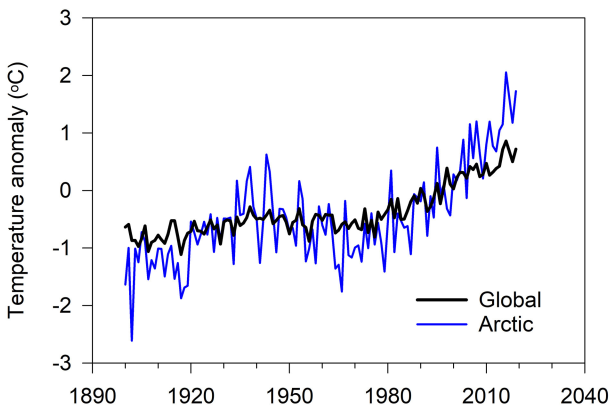

FIGURE 2 | 'Arctic' (land stations north of 60° North latitude) and global annual surface air temperature anomalies 1900–2019 (°C) relative to the 1981–2010 regional mean values. Updated from Overland et al. (2017).

taiga and boreal forests where reindeer and caribou, their North American conspecifics (**Box 1**), graze. The effects of warming include the stimulation and an advance of the timing (phenology) of photosynthetic activity (Xu et al., 2013; Fauchald et al., 2017; Park et al., 2019) and the modulation of snow cover (AMAP, 2017), all of which are associated with variation in individual and population rates of growth (Tyler et al., 2008; Post et al., 2009b; Mallory and Boyce, 2018). Considering the latter (i.e., human intervention), the principal negative effects on reindeer pastoralism seem not to have arisen primarily through deliberate, large-scale slaughter of animals, as in the case of the other species of large ungulates given above, but as a consequence of legislation developed and imposed for political, economic and other reasons (although see Vitebsky, 2005, p. 406). The compulsory organization of reindeer pastoralism in collective (*kolkhoz*) and State (*sovkhoz*) farms in the Soviet Union from the 1920s until the 1990s (or even, in some cases, to the present day: see Kumpula et al., 2011) is a conspicuous example. Collectivization not only disrupted the lifestyles and the cultural, economic and spiritual values of herding peoples throughout the region, it also anticipated the demise of herds following the abandonment of this form of organization at the fall of Russian Communism in 1991 (Vitebsky, 2005; Anderson, 2006; Povoroznyuk, 2007; Klokov, 2011; Konstantinov, 2015). Less conspicuous but no less pervasive were—and still are—the effects on reindeer pastoralism of the loss of pasture and the disruption of movement of herds and herders owing to the expansion of infrastructure and commercial, military and private activity into reindeer pasture areas. Modern examples include the direct and cumulative impact of oil, gas, mining, wind- and hydro-electricity and other infrastructure developments in northern pasture areas since the 1970s (Dwyer and Istomin, 2009; Forbes et al., 2009; Degteva and Nellemann, 2013; Tolvanen et al., 2019). We return to this below.

The problem of range loss and the disruption of reindeer herding is not new. Disagreements between Saami reindeer herders and other users over rights of access and rights of use of reindeer pasture (*utmark*; **Box 2**) in Norway can be traced back at least 150 years (Strøm Bull, 2015). Domesticated reindeer in Norway graze and are grazed exclusively in *utmark* but herders' rights of usufruct have repeatedly been challenged (below). Solutions have been sought in the courts and through legislation aimed at regulating and, through regulation, at managing Saami reindeer pastoralism. This has been done with the specific intention of addressing problems—real or perceived—associated with it, including disputes over grazing rights, low productivity, poor animal welfare associated with the use of traditional methods and the environmental impact of reindeer pastoralism. The addressing of such issues has resulted in Saami reindeer pastoralism in Norway becoming an administrative and economic burden for national and local legislatures, in addition to which an unrelenting focus on issues deemed problems has led to profoundly negative political and public discourse: Saami reindeer pastoralism in Norway is perceived as persistently problematic (**Box 2**).

A decade ago it was suggested that the effects of human intervention and, in particular, of the reduction of herders' freedom of action resulting from loss of pasture through various forms of encroachment and from aspects of governance related to this, dwarfed the putative effects of climate change on reindeer pastoralism in Norway (Tyler et al., 2007). The model was specific but its conclusion appears to be general: there is increasing evidence that the effects of various forms of human intervention not unusually far exceed the effects of climate change on pastoral systems (e.g., Hobbs et al., 2008; Havlík et al., 2015; Ahmed et al., 2016; López-i-Gelats et al., 2016). Here we review the conclusion of the reindeer model. First, we extend parts of the analysis upon which it was based by externally validating and testing the predictive power of current projections of regional climate change. (For the difference between projections and predictions of climate, see **Box 3**). Second, we examine spatial and temporal trends in local weather conditions around Finnmarksvidda, which is the principle reindeer winter pasture area in Norway (**Figure 7**). Third, we review the gradual but erratic liberalization of Saami grazing rights since the mid-18th Century and the current administrative curtailment of herders' rights and freedom of action in herding and herd management. Finally, we review avoidance behavior and the effects of infrastructure on the use of habitat by reindeer. We conclude that the role of climate change as a driver of change in grazing conditions—and by extension as a driver of change in reindeer pastoralism—is unclear except insofar as it is spatially and temporally highly diverse. The effects of human intervention on reindeer pasture in northern Norway, by contrast, are consistently negative. Saami pastoralists struggle with loss of pasture resulting from encroachment and with restrictions and reorganizations that erode their independence and constrain their freedom of action on the pasture areas that remain available to them. The effects of human intervention seem far to exceed the effects of climate change on the system. This situation is not unique: loss of pasture and myriad administrative,

BOX 2 | The pastoral system: Saami reindeer herding in Norway

There are ~215,000 domesticated reindeer in Norway (data for 2019: Norwegian Agriculture Agency, 2019a). The majority (94%) of these are herded by Saami pastoralists who graze their animals on 141,000 km^2 of *utmark* designated as Saami reindeer pasture (Government of Norway, 2017; **Figures 3**, **4**). (*Utmark*, pronounced 'oot-mark', is a Norwegian word for uncultivated land, including forests, meadows, moorland and mountains). The majority (80%) of reindeer in this area live in the Troms, East Finnmark and West Finnmark reindeer pasture areas (which together constitute the single country of 'Troms and Finnmark'; **Figure 3**). A minority (6%) of reindeer in Norway are herded by Saami and non-Saami Norwegians in *utmark* in the south of the country outside the Saami reindeer pasture area (Government of Norway, 2017; marked as 'Other areas' in **Figure 3**).

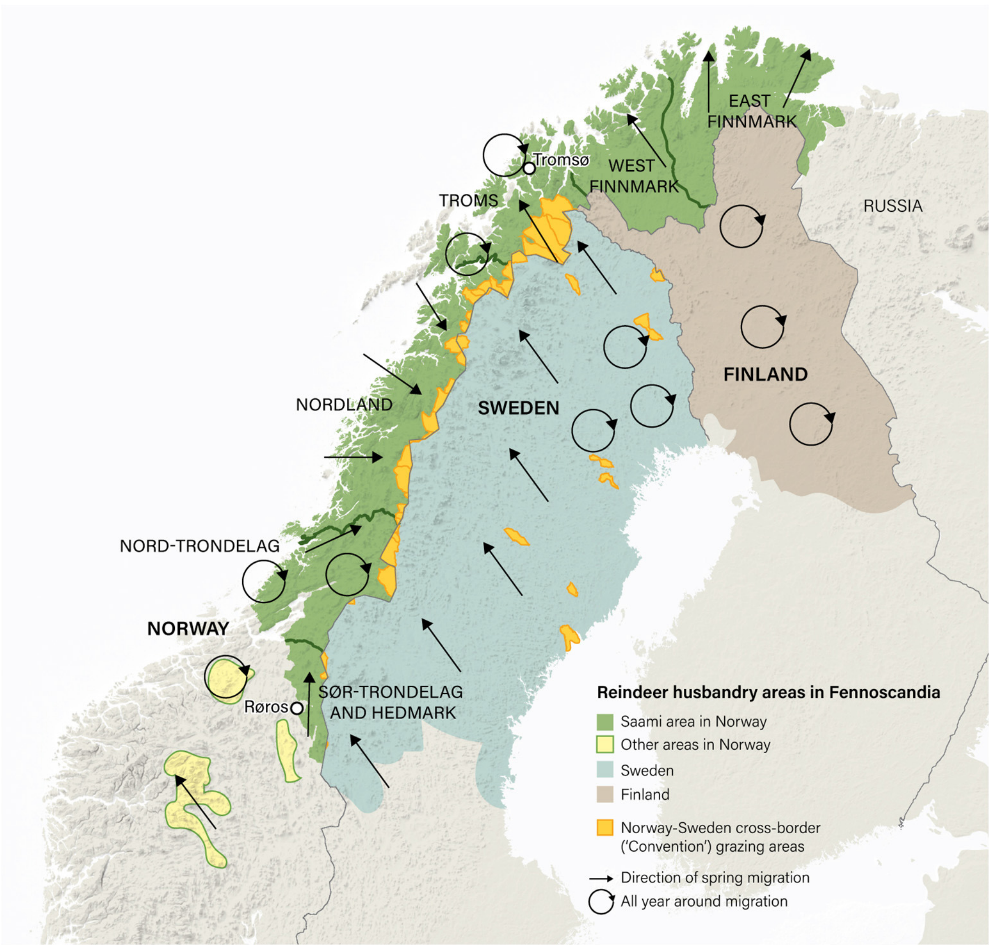

FIGURE 3 | Saami reindeer pastoralism in Norway, Sweden and Finland. The Saami reindeer husbandry area in Norway (green shading) constitutes 141,000 km^2 of *utmark* (uncultivated land, including forests, meadows, moorland and mountains). This area is equivalent to 40% of the entire country. It is in turn divided into six 'reindeer pasture areas' (Troms, East Finnmark, West Finnmark, Nordland, Nord-Trøndelag and Sør-Trøndelag and Hedmark). The map also shows the reciprocal cross-border ('Convention') grazing areas used by Norwegian Saami in Sweden and *vice versa* (orange shading). These constitute an area of ~14,000 km^2. The Convention on cross-border grazing between Norway and Sweden is currently in abeyance (see text). Sources: Government of Norway (2010) and Pape and Löffler (2016).

The Saami reindeer pasture area in Norway is divided into six 'reindeer pasture areas' (of which Troms, East Finnmark and West Finnmark are the most northerly; **Figure 3**). These six areas are in turn divided into altogether 82 'grazing districts'. These administrative divisions are government, not Saami, constructs. Within each district, groups of reindeer owners—members of one or more families—keep their reindeer in combined herd(s) which they manage collectively. Herding alliances ('*siida*' and '*sijte*' in northern and southern Saami language, respectively) may persist across all or just part of the year. A particular summer *siida* may, for instance, routinely divide in autumn, with some herders (and their reindeer) joining another *siida* for winter. Currently there are around 100 and 150 different summer and winter *siida*, respectively, in Norway (Government of Norway, 2017). This dynamic is possible because every reindeer is the property of a particular owner, not a particular *siida*. Ownership is established by a pattern of ear marks, each unique to an owner, that provide permanent identification of animal ownership (**Figure 4**).

BOX 2 | continued.

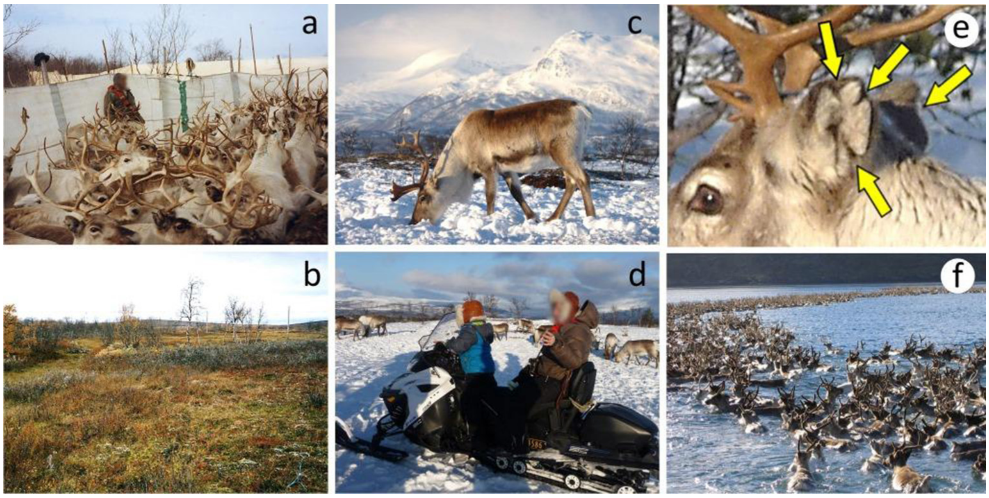

FIGURE 4 | Saami reindeer pastoralism in Norway. **(a)** The late Mathis Aslaksen Sara with his family's reindeer in a temporary paddock at Cuovddatmohkki (**Figure 7**). This paddock was erected in April (2002) to enable his and another family to separate their herds which, after wintering together, were about to move independently to their summer pasture on the island of Magerøya (**Figure 7**). **(b)** The same site 5 months later (September 2002): virtually no trace remains either of the paddock or of the presence of the hundreds of reindeer which had been gathered in it. Grazing rights accrue through the legal principle of 'use since time immemorial' (Norwegian: *alders tids bruk*) but, as photograph **(b)** shows, it may be no simple matter for pastoralists to document their use of an area. **(c)** A pregnant reindeer on winter pasture in northern Norway. The snow all around the animal has been excavated by reindeer which have been feeding on the plants beneath. **(d)** Reindeer herder and her son inspecting their herd in the same area. **(e)** Ear marks (yellow arrows) permanently and indelibly identify the ownership of every reindeer in a herd. Each owner has his or her own unique pattern of marks which are cut into the left and right ears of animals in their first summer and which they bear for life (see Paine, 1994, p. 24; Beach, 2007). **(f)** Transhumant pastoralism: 3,000 reindeer swim in September (2004) from their summer pasture on the island of Magerøya to the mainland at the start of their 200 km autumn migration to winter pasture south of Cuovddatmohkki on Finnmarksvidda (**Figure 7**). Magerøya Sound is ~1,200 m wide at this point. Photographs: Nicholas Tyler.

FIGURE 5 | Divided discourse: a selection of cuttings illustrating contrasting opinions about reindeer pastoralism in Norway. Translations are as follows. *On the left*: Reports reindeer herders [to the police]; Finnmarksvidda is being destroyed—abolish reindeer husbandry; Senior member of the Progress Party on reindeer husbandry: economic swindle and animal cruelty; Reindeer starving to death; Marginal loss… [of reindeer pasture owing to mining at] Repparfjord; Thin reindeer

(Continued)

BOX 2 | continued.

Figure 5| fall prey to predators; Fear catastrophic starvation; Serious animal cruelty exposed in reindeer husbandry; The anticipated tragedy; Reindeer eat up garden [plants]; This reindeer calf is starving to death; Demands removal of reindeer from island [pastures]; The myth of lost pasture land in Finnmark; Sustainable reindeer husbandry has not been achieved. *On the right*: School book criticized for stigmatizing reindeer husbandry; Let the mountain live!; Beginning of the end of reindeer husbandry; Norwegian herder ordered to put down dozens of reindeer in controversial cull; Rudolf's relatives given a death sentence: Norway orders mass reindeer slaughter before Christmas; Scientists evasive about reindeer husbandry; Threaten Mikkel Mathis with a colossal fine to make him slaughter his reindeer; In Norway, fighting the culling of reindeer with a macabre display; Reindeer pastoralism considers court action; 'Celebrity' herd threatened by the Nussir mine; No one listens to reindeer herders—I don't know what we'll do now; The State defeated Jovsset Ánte in the Supreme Court; Swedish Saami institute legal proceedings against the [Norwegian] State [over]… grazing rights… aim to stop social Darwinism; Saami culture must be prioritized!; Not surprising that the Saami are furious.

Saami reindeer pastoralism in Norway is typically, but not invariably, transhumant. The Saami enjoy the right of usufruct throughout the Saami reindeer pasture area. *Siida* with anything from 100–10,000 reindeer of mixed age and sex normally move between discrete summer and winter pastures. Summer pastures are usually, although not invariably, at the coast where mild, humid weather favors plant growth. Winter pastures are usually, although not invariably, at higher elevation inland where winters are colder and the snow tends to remain dry and friable and hence easier for the animals to dig through to reach the plants beneath. The reverse pattern of migration occurs where low lying coastal pastures remain largely free of snow in winter and where inland mountains provide mild, humid conditions in summer. There are also places where reindeer remain in the same area all the year round, largely performing only altitudinal migration (**Figure 3**).

In contrast to domestic species, which in Norway remain indoors all winter, reindeer remain outdoors, grazing natural pasture all year round. The animals usually receive minimal attention in summer. This is especially the case where herds are swum or ferried to islands or led onto peninsulas before calving spring, and where they remain, undisturbed, until they are gathered for the return journey in autumn (**Figure 4**). Close herding is normally practiced only during migration and throughout winter when herders move their animals frequently in response to snow conditions and to the presence of other herds.

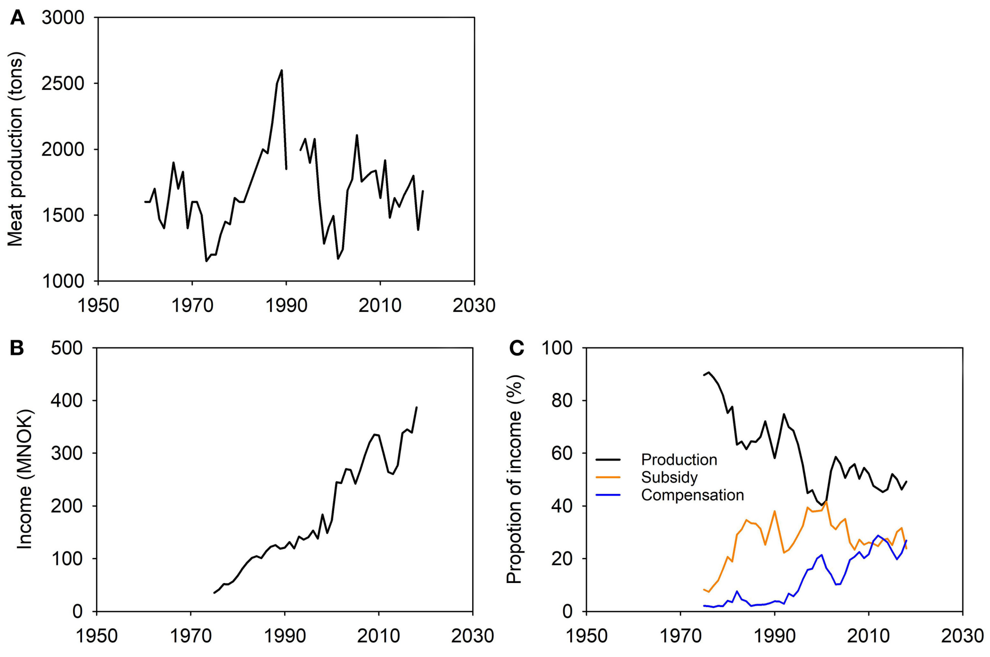

FIGURE 6 | Production and income in reindeer pastoralism in Norway (Saami and non-Saami combined). **(A)** Annual production of meat (tons). **(B)** Annual income (MNOK). **(C)** Proportion of income from each of three sources: production, State subsidies and State compensation. Sale of meat accounts on average for 90% of production income while on average 83% of compensation is paid for reindeer lost to predators. Sources: Government of Norway (1992), Norwegian Agriculture Agency (2019a), and Norwegian Reindeer Husbandry Administration (2006).

Reindeer pastoralism has considerable economic, social and cultural significance for Norwegian Saami. Its principal economic product now, although not historically, is meat. The level of production of reindeer meat is the same today as it was in 1960 (1960: 1,600 tons; 2018/19: 1,683 tons; Government of Norway, 1992; Norwegian Agriculture Agency, 2019a; **Figure 6**). In 2018 meat and other products had a value of NOK 123 million and NOK 67.5 million (~US$ 18 and 10 million, respectively), equivalent to 49% of the total income of reindeer pastoralism that year (NOK 387 million). Income also derives from government subsidies (NOK 92.5 million, 24%) and compensation (NOK 104 million, 27%) for animals lost to predators (NOK 92 million) and for pasture lost through encroachment (NOK 12 million; Norwegian Agriculture Agency, 2019b, p. 2). Saami reindeer husbandry in Norway is beset by conflict and criticism (**Figure 5**). Pastoralists' rights of usufruct, ultimately confirmed following 100 years' tortuous passage through the courts (see main text), are still challenged, albeit informally but no less bitterly (e.g., Anonymous, 2009; Lysvold, 2017). Public opinion is divided. Claims of 'overpopulation' and 'overgrazing' (e.g., Government of Norway, 1992; Office of the Auditor General, 2004; Vogt, 2007; Anonymous, 2012, 2014, 2015a; Hætta, 2018; Enoksen, 2019) are met with counter-claims of misunderstanding and political bias (Benjaminsen et al., 2015, 2016a,b; Benjaminsen, 2018; Benjaminsen et al., 2019).

BOX 2 | continued.

Poor rates of production are attributed to high stocking density not predators (Kintisch, 2014) and to high levels of predation not stocking density (Berg, 2018). Allegations of poor animal welfare (e.g., Gauslaa, 2001; Grøndahl and Mejdell, 2012; Lund, 2017; see also Anonymous, 2015b) are symptomatic of dissatisfaction with reindeer pastoralism (e.g., Salvesen, 2009; Ringjord, 2016; Bergersen, 2017) that is anathema to its adherents (e.g., Sara, 2001; Anti, 2017; Fjellheim, 2020).

BOX 3 | Meteorological terms, models and data

Climate and Weather

Weather is the day-to-day state of the atmosphere. It is, generally speaking, the combination of temperature, humidity, precipitation, cloudiness, visibility and wind that we experience instantaneously at a given place at a given time.

Climate is a description of the probability of particular kinds of weather at a given place at a given time. It is a statistical norm calculated over a period of time, usually 30 years, and includes not only middle values but also the characteristic level of deviation around statistical middle values. The climate of a particular location, region or zone is thus defined in terms of the long-term averages and the frequencies of different kinds of weather conditions observed within it. The popular aphorism is apt: Climate is what you expect: weather is what you get.

Spatial variation in climate arises as a consequence of latitude, topography and the distribution of land and water (sea or lake). Ambient temperature, for instance, normally decreases with increasing latitude and altitude (although cold air tends to descend and fill depressions in the terrain when the sun is below the horizon and the air pressure field connected to the large-scale circulation, and hence wind, is weak). Inland areas tend to be warmer in summer and colder in winter than coastal areas. When the large-scale circulation is strong, the windward side of mountain areas may be exposed for orographic enhanced precipitation while the leeward side experiences a 'rain shadow' with low precipitation and few clouds.

Temporal variation in climate is in part a product of external and internal forcing at various time scales. Forcing may be natural or anthropogenic. External forcing, such as variation in solar radiation or in the concentration of greenhouse gases, lead to changes in the total energy budget of the Earth-atmosphere system. Internal forcing mainly affects the distribution of energy within the Earth-atmosphere system such as, for instance, between the atmosphere and the ocean. Some of the temporal variation in climate is random, while some of it seems to be relatively regular with distinct patterns and phases of temperature and other weather variables. Such patterns, captured and quantified in 'climate indices,' may be quasi-periodic: i.e., they oscillate at more or less distinct frequencies measurable at annual, multi-annual, decadal or multi-decadal timescales. Examples include the El Niño–Southern Oscillation (ENSO), the Madden–Julian Oscillation (MJO), the North Atlantic Oscillation (NAO), the Northern Annular Mode (NAM) or Arctic Oscillation (AO) and the Pacific Decadal Oscillation (PDO). For Norway, the NAO and AO are the most important. Positive values of the NAO and AO indices indicate stronger-than-average westerlies over middle latitudes, leading to mild winters and, especially in western regions, abundant precipitation while negative values indicate the reverse (Hanssen-Bauer et al., 2005) [For details about the various indices see Anonymous (no date)].

Climate Projections and Climate Predictions

Climate models and weather forecast models are numerical systems based on equations that attempt to capture principal features of the climate system: they are, however, used in different ways. A weather forecast is a prediction. It aims to predict the weather a few days ahead at specific sites as accurately and reliably as possible. Weather forecasting is therefore based on detailed descriptions of the current weather that are fed into models that calculate the development of the weather day by day and even hour by hour. Climate models, by contrast, are used to calculate weather statistics under different boundary conditions (such as the concentrations of greenhouse gases in the atmosphere). Such models do not aim to predict the weather on a particular day or even the average weather for a particular season or year; rather, they aim to calculate the long-term weather statistics under given boundary conditions. They generate climate *projections*, not climate *predictions*, because they are based on boundary conditions which may or may not ever actually arise.

Projections of global climate change under different emission scenarios are based on global numerical models of the climate system. Results from different climate models are compared in the Coupled Model Intercomparison Project (CMIP). The fifth assessment report from the Intergovernmental Panel on Climate Change (IPCC, 2013) is based on results from the 5th phase of this project, CMIP5. The results are projections of change in global and continental scale climate under four scenarios called 'Representative Concentration Pathways' (RCPs; IPCC, 2013). The moderate RCP4.5 scenario, which is applied in the estimates in this paper, lies between the low emission RCP2.6 scenario and the 'business as usual' RCP8.5 scenario. Average (mean or median) values from the CMIP5 ensemble exemplify potential changes in large-scale climate under particular RCPs. The 10 and 90 percentiles of the ensemble are often used to indicate the level of uncertainty in the projections.

Meteorological Data in the Present Study

Meteorological Stations

The data presented here are drawn from the six meteorological stations that are within or near the reindeer winter pasture area of Finnmarksvidda, Norway (**Figure 7**). All were originally manned stations but Suolovuopmi, Karasjok and Sihccajarvi were automated in 2005, 2005 and 2009, respectively. The station at Kautokeino has been relocated twice during the last 50 years and the temperature data have been adjusted to compensate for this, thereby ensuring the homogeneity of the data time-series.

Study Period

Most weather data have a large stochastic component and long-term trends in weather (the signal) are therefore liable to be obscured by short-term random variation (noise). Detecting trends therefore requires analysis of long time-series, especially where the trends are weak. Weather records collected at remote stations, however, are frequently incomplete which reduces the number of datasets available if very long length is an absolute requirement. Here we have used a period of 50 years (1969–2018). This is a compromise but it spans the period in which significant anthropogenic influence on the climate has been recognized (IPCC, 2013) and it proved long enough to reveal both decadal variation and significant trends in the weather.

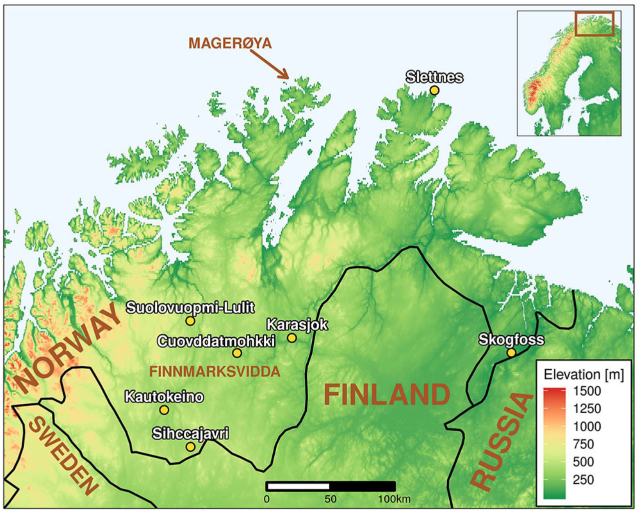

FIGURE 7 | Meteorological stations within the reindeer winter pasture area of Finnmarkvidda at which the data presented here were collected. These are Cuovddatmohki (station number 97350, 286 m a.s.l.), Kautokeino (93700, 307 m a.s.l.), Karasjok (97250, 131 m a.s.l.), Sihccajarvi (93900, 382 m a.s.l.), Skogfoss (99500, 55 m a.s.l.) and Suolovuopmi (93300, 381 m a.s.l.). Data for weather conditions during calving time (May) were collected at Slettnes Lighthouse (96400, 8 m a.s.l.).

economic legal and social constraints are a feature not only of Saami reindeer husbandry but of extensive pastoral grazing systems across the globe.

THE INFLUENCE OF CLIMATE AND WEATHER ON ANIMAL PERFORMANCE

The Climate Paradox

The influence of environmental variation—specifically, the supply of water and forage—on the productive performance of large ungulates has been recognized and recorded for millennia. The effect of drought on domestic animals in the semi-arid grasslands of the Middle East is vividly described in the Book of Joel, parts of which date from the early 8th Century B.C. (Allen, 1976) and in Hittite mythology of even greater antiquity (Bryce, 2002). Large annual and multi-annual fluctuations in the performance of animals in response to corresponding fluctuation in the weather is a feature of extensive grazing systems everywhere (e.g., Clutton–Brock and Pemberton, 2004; Thornton et al., 2009; Megersa et al., 2014; de Araujo et al., 2018).

Interest in the influence of environmental variation on animal performance has increasingly focussed on the role of climate change as an ecological driver. Indeed, the biological basis of the dynamics of wild populations and of production in extensive grazing systems is now rarely considered in any other context. This is a paradox because organisms—specifically, grazing animals and the plants on which they feed—do not respond to large-scale climate *per se*. Rather, they respond explicitly to those features of the thermal environment that impinge on them, their resources, their competitors, their predators and their parasites. The growth, survival and productive performance of grazing animals and the plants they eat are modulated by ambient temperature, radiation, wind speed, precipitation and other factors which together constitute the physical conditions of their immediate environment or, more simply, the weather (Mount, 1979; WMO, 2010). Weather and climate are different concepts (**Box 3**) and large-scale climate has no bearing on the performance of organisms except insofar as it influences the conditions to which they are exposed and to which they respond.

Indices of large-scale climate such as the North Atlantic Oscillation (NAO) or the El Niño–Southern Oscillation (ENSO; **Box 3**) are nevertheless routinely incorporated within analytical models of animal performance. There are several reasons for this. First, they are regularly updated and are available free of charge on the web. Second, unlike local weather data, they are spatially extensive and therefore afford investigators a common numerator with which to evaluate ecological responses to variation in environmental (meteorological) conditions over large spatial scales (e.g., Post and Forchhammer, 2002, 2004; Stige et al., 2006; Post et al., 2009a; Ascoli et al., 2017; Hagen et al., 2017). Climate indices also represent convenient environmental metrics for use at remote locations where there are no weather stations, and hence no weather data, for the same reason (e.g., Forchhammer et al., 2002). Finally, climate represents an integration of the thermal environment and indices of climate may therefore capture associations between environmental conditions and ecological processes better than more precise metrics (e.g., monthly averages of local weather variables; Hallett et al., 2004; Knape and de Valpine, 2011). The usefulness of indices of large-scale climate in *post hoc* accounting of variation in the growth and performance of organisms has been demonstrated many times in many taxa, and the expediency of incorporating such indices in analyses which aim to determine the consequences of climate change for species and ecosystems has repeatedly been emphasized (e.g., Raynor et al., 2020).

It is nevertheless also clear that this approach has limited predictive power. The impact of global warming on particular species of large ungulates varies widely across space and time. Effects of climate change on the physical growth of individuals, and on the numerical growth of populations, vary from positive to negative and from weak to strong across the distributional range of species (i.e., between populations) and over time (Mysterud et al., 2001; Tyler et al., 2008; Post et al., 2009a; Joly et al., 2011; Uboni et al., 2016; see also Krebs and Berteaux, 2006). Spatial and temporal variation in the strength and form of responses of a species to variation in large-scale climate reflects spatial and temporal variation in the relationship between large-scale climate and the weather (Post, 2005; Zuckerberg et al., 2020) and in local ecological settings (Martínez–Jauregui et al., 2009). Predicting the magnitude and the sign of responses of large ungulates to changes in climate therefore requires more information than is contained in summary indices. It is necessary, for instance, to confirm that components of the weather which actually influence the metabolic state of focal species (plants or

BOX 4 | How weather influences performance: relationship between the intake, loss and retention of energy

Energy in the food animals eat may be used to fuel chemical and mechanical work, whence it is lost to the environment, or it may be retained in body tissue. Retention of energy, realized as growth and fattening, influences survival and, where energy is exported as offspring and milk, also production.

The relationship between the intake, retention and loss of food energy is:

$$\mathrm{MEI} = \mathrm{ER} + \mathrm{H} \quad (1)$$

where MEI is metabolizable energy intake, ER is energy retained in body tissue and H is energy (heat) lost to the surroundings. When an animal is in thermal equilibrium (i.e., when there is no change in its mean body temperature), its rates of heat production and heat loss are necessarily equal. From Equation 1 it follows that if the animal's rate of intake of metabolizable energy in this state equals its rate of heat loss (i.e., MEI = H), then energy retention is zero (ER = 0). This level of intake is known as 'maintenance'. Super-maintenance intake, where metabolizable energy intake exceeds the rate of heat loss (MEI > H) results in net retention of energy (ER > 0) and hence growth and production. Sub-maintenance intake (MEI < H) results correspondingly in weight loss (ER < 0) as the deficiency in energy is made good through mobilization of body tissue, including fat reserves.

animals) correlate with, and hence may reasonably be assumed to be a function of, indices of large-scale climate. It is also necessary to confirm that climate related variation in local weather conditions is physiologically relevant. Heat loads (hot or cold) imposed by statistical extremes of ambient temperature, for instance, are likely to have a measurable impact on the performance of an animal only where they fall outside its thermoneutral range (Mount, 1979; Blaxter, 1989). The omission of either step from analyses that aim to explore the consequences of climate change for a particular population of a species confines results within the realm of attractive but inconclusive association (Seebacher and Franklin, 2012; Cooke et al., 2013).

Local Conditions: Influence of Weather on the Performance of Reindeer

Effects of weather conditions on the performance of animals derive from situations in which meteorological factors like solar radiation, ambient temperature, rainfall and wind speed modulate the flow of energy to or from them and hence also the amount of energy they retain and can allocate to growth and production (**Box 4**). Effects of weather conditions on energy flow may be either direct or indirect. Direct effects involve the modulation, by the weather, of any one of four channels of heat flow from the animal to the environment (i.e., convection, conduction, radiation or evaporation; Mount, 1979). Indirect effects are chiefly associated with variation in energy supply which, for herbivores, normally means modulation of the growth and chemical composition of forage plants and, at high latitudes or altitudes, of the availability of forage beneath snow.

Direct Effects

The boreal region is cold: the mean ambient winter (October to April) temperature throughout the distributional range of *Rangifer* is 40–50°C below the species' body temperature. (The rectal and brain temperatures of *Rangifer* resting or standing at ambient temperature within their thermoneutral zone ≈38°C; Blix and Johnsen, 1983; Mercer et al., 1985; Blix et al., 2011.) The large temperature gradient between the animals and the environment renders them potentially susceptible to hypothermia. However, low temperatures and high wind speeds have only a small effect on the rate of heat loss—and hence on performance—in this species because the animals are exceedingly well adapted to the cold. Their thick winter coat, with hollow guard hairs filled with a honeycomb of air-filled cavities separated by thin septa (Timisjarvi et al., 1984; Blix et al., 2015), provides superb insulation (Nilssen et al., 1984) even in strong wind (Cuyler and Øritsland, 2002). Consequently, with the exception of newborn calves, it is most unlikely that *Rangifer* ever suffer hypothermia except perhaps under the most severe weather conditions or when starving (Blix, 2016; Tyler, 2019). Newborn *Rangifer*, by contrast, are highly susceptible to windchill and hence hypothermia. Calves are born in May and early June at which time cold, wet, windy conditions, coincidental with the spring melt, generally prevail. For example, the mean May temperature and precipitation at Slettnes Lighthouse (station 96400, **Figure 7**), representative of coastal calving areas for reindeer in northern Norway, are +3.4°C (SD 2.8°C) and 35 mm (SD 18 mm), respectively (temperature data for 1969–2019 and precipitation data for 1969–2003 from the Norwegian Meteorological Institute). Calves are precocious (Blix and Steen, 1979) but their light brown natal coat provides poor thermal protection especially when wet (Markussen et al., 1985). Their principal defense against cold is to increase heat production by mobilizing deposits of thermogenic brown adipose tissue with which they are born (Soppela et al., 1986, 1991, 1992; Blix, 2016) but harsh weather at calving may result in substantial mortality from hypothermia (Kelsall, 1968, p. 238; Miller et al., 1988).

Indirect Effects

Indirect effects of weather conditions on the performance of *Rangifer* are remarkable for their heterogeneity: seasonal warming, and the increase in precipitation associated with it, can have both positive and negative effects on the animals.

Warm weather in spring and summer in a region where summers are usually cold encourages earlier and faster growth of tundra plants (Elmendorf et al., 2012; Myers-Smith et al., 2019; but see Gustine et al., 2017) and warming across the last four decades has consequently resulted in widespread greening of the Arctic (Pattison et al., 2015; Zhu et al., 2016; but see

Lara et al., 2018). Consistent with this, mild spring weather and earlier snow melt are associated at some sites with increased availability of forage, earlier onset of plant growth, increased primary production and, in turn, earlier calving (an advance of ∼7 days over 45 years in Finland: Paoli et al., 2018) and increased body mass of animals in autumn (Norway: Pettorelli et al., 2005; Tveraa et al., 2013; Albon et al., 2017; Canada: Couturier et al., 2009). At other sites, however, warming has negative effects. Mild weather in spring (May and June) has been associated with heavy mortality of caribou, owing to the formation of ground (basal) ice that restricts the animals' access to forage (Canadian high-Arctic: Miller et al., 1982; Woo et al., 1982), and to trophic mismatch (i.e., the uncoupling of phenological events within food chains; see Visser et al., 2010; Kerby et al., 2012). The negative effect of trophic mismatch on cervids has been attributed to disruption, by an advance in the emergence of forage, of the phase relationship between the seasonal pulse of primary production and the seasonal demand for nutrients in lactating females (Kerby and Post, 2013; Plard et al., 2014). Thus, an advance in the spring emergence of plants of ∼10 days over 5 years was associated with declines in the rates of production and survival of caribou calves in West Greenland of ∼75% (Post and Forchhammer, 2008; Post et al., 2008, 2009b).

Winter warming, likewise, has both positive and negative effects on performance in *Rangifer*. These derive from the different ways in which warm weather modulates the snowpack and, hence, the animals' access to forage. This especially important for *Rangifer* because females are pregnant throughout winter (the animals mate in October and give birth in May or early June) and therefore have to meet the metabolic requirements of gestation at a time when access to forage is restricted by snow (LaPerriere and Lent, 1977; Skogland, 1978). Warming stimulates the hydrological cycle and has led to an increase in the average level of precipitation at mid-to-high northern latitudes across the last century (Stocker et al., 2014). Enhanced poleward moisture transport at high latitudes amplifies this trend (Zhang et al., 2013). Increased precipitation in the boreal zone can lead to increased accumulation of snow which, in turn, is associated with reduced body mass of calves at birth and also subsequently at weaning (Adams, 2005; Couturier et al., 2009; Hendrichsen and Tyler, 2014). The negative effect of snow on birth weight reflects reduction of dams' food intake and increased energy expenditure during pregnancy owing to restriction of their access to forage and to the high energy cost of walking through and digging snow to find food, respectively (Thing, 1977; Fancy and White, 1985; see also Ossi et al., 2015). This may lead to reduced allocation of nutrients to placental and fetal growth and hence to reduced birth weight (Redmer et al., 2004; Wu et al., 2006; Wallace et al., 2010). The negative effect of snow on weaning weight is presumably a result of fetal programming (Lucas, 1991; Rhind et al., 2001) and to reduced growth of forage plants (above). Increased accumulation of snow may also, however, enhance early postnatal growth. This occurs where the prolonged duration of the melt, reflecting the greater mass of snow that has to melt, extends the period of emergence of plants and hence the length of time in which the animals find and feed on freshly emerging highly nutritious shoots (Mårell et al., 2006, Leffler et al., 2016). That this positive effect of increased accumulation of snow in winter on growth of animals in summer, evident in red deer *Cervus elaphus* and sheep (Mysterud and Austrheim, 2014), has not been detected in *Rangifer* (e.g., Pettorelli et al., 2005) presumably reflects the complexity of the spatio-temporal dynamics of forage and foraging on the floral mosaic of tundra-taiga pastures (Skogland, 1980, 1984, 1989; White, 1983; Mårell and Edenius, 2006; Mårell et al., 2006; Gustine et al., 2017).

Interludes of warm weather and rain in winter that modulate the availability of forage by restructuring the snowpack are another feature of weather conditions which has both positive and negative effects on the performance of *Rangifer*. Warming that results in the formation of layers of ice in the snowpack or on the ground beneath it may reduce the availability of forage causing weight loss and starvation (Albon et al., 2017; Eira et al., 2018). Such 'icing' is held to cause of heavy mortality in *Rangifer* (e.g., Putkonen and Roe, 2003; Bartsch et al., 2010) although the empirical evidence for the generality of this effect is surprisingly weak (Tyler, 2010; Hansen et al., 2011; Forbes et al., 2016). By contrast, the intensity of such interludes, and the thawing they cause, is on occasion sufficient to melt snow away, exposing the vegetation and, by thus increasing the availability of forage (Vibe, 1967; Damman, 1983; Mahoney and Schaefer, 2002), enhancing survival and reproduction and stabilizing the dynamics of populations (Tyler et al., 2008; Hansen et al., 2019a).

Weather conditions thus influence the performance of *Rangifer* in different ways and through effects that can be measured at many different scales: locally, regionally, even continentally. Usually what matters to people and animals most, however, is the weather local to where they are, will or might wish to be. The central issue for the present study is the extent to which trends in climate that are conventionally assessed at regional, zonal or global scale, actually influence weather conditions locally within Saami herding areas. This is the topic of the next section.

METEOROLOGICAL CONDITIONS AT REINDEER WINTER PASTURE IN FINNMARK: PROJECTED AND OBSERVED CLIMATE CHANGE

Projections: Past and Future Trends in Climate

The boreal zone is currently warming. Climate projections (**Box 3**) indicate that the warming is likely to continue for the foreseeable future (Christensen et al., 2014). Such projections, based on global climate models, have coarse spatial resolution (typically 100–200 km between the grid-points). Pastoralists and biologists alike, however, are chiefly interested in the conditions which affect plants and animals locally. Local conditions are a product of interaction between large-scale climate and local topography and generating local climate projections consequently requires a further stage of analysis. Results from the global models are downscaled by taking account of climate-landscape interactions through procedures known as Empirical Statistical Downscaling (ESD; Benestad et al., 2008) and Regional Climate Modeling (RCM; Anonymous, 2019).

The median projection for the mean annual temperature of Finnmarksvidda (**Figure 7**), based on 10 RCMs and modelled under the RCP4.5 emission scenario (see **Box 3**), indicates an increase of 2.5°C across the period 1971–2000 to 2030–2060, equivalent to a rate of warming of 0.4°C · decade^{-1} (**Figure 8A**, **Table 1**). This projection closely matches the trend of warming observed across the region since the 1980s (**Figures 8A,C**). The corresponding projection for annual precipitation indicates an increase of 40 mm (7%) across the same period, equivalent to 7 mm · decade^{-1} (1.5% · decade^{-1}, **Figure 8B**). The trend in precipitation actually observed across the region, however, is currently more than twice this (about 3.5% · decade^{-1}) and exceeds all but the upper part of the ensemble of projections (**Figures 8B,D**).

Projections for the duration and depth of snow cover, produced by running a hydrological model with input from the projections for temperature and precipitation (Hanssen-Bauer et al., 2015, 2017), show a reduction in the length of the snow season all over Norway. The effect is most marked over coastal lowlands but is also apparent over inland mountain areas (Hanssen-Bauer et al., 2015, 2017). For Finnmarksvidda, the RCP4.5 scenario typically gives a reduction in the period of snow cover of 1–2 months from 1971–2000 to 2071–2100 which, if the trend were linear, would be equivalent to a rate of 3–6 days · decade^{-1}.

Projections for maximum snow depth (measured as 'water equivalent,' mm) show only small changes over Finnmarksvidda toward the end of the 21st Century (Hanssen-Bauer et al., 2015, 2017). These include a small reduction for most of the area but also minor increases at some sites (which vary from model to model). In neither case are the trends likely to be linear because snow depth is a function of both precipitation and temperature. Hence, snow depth is likely initially to increase with increasing

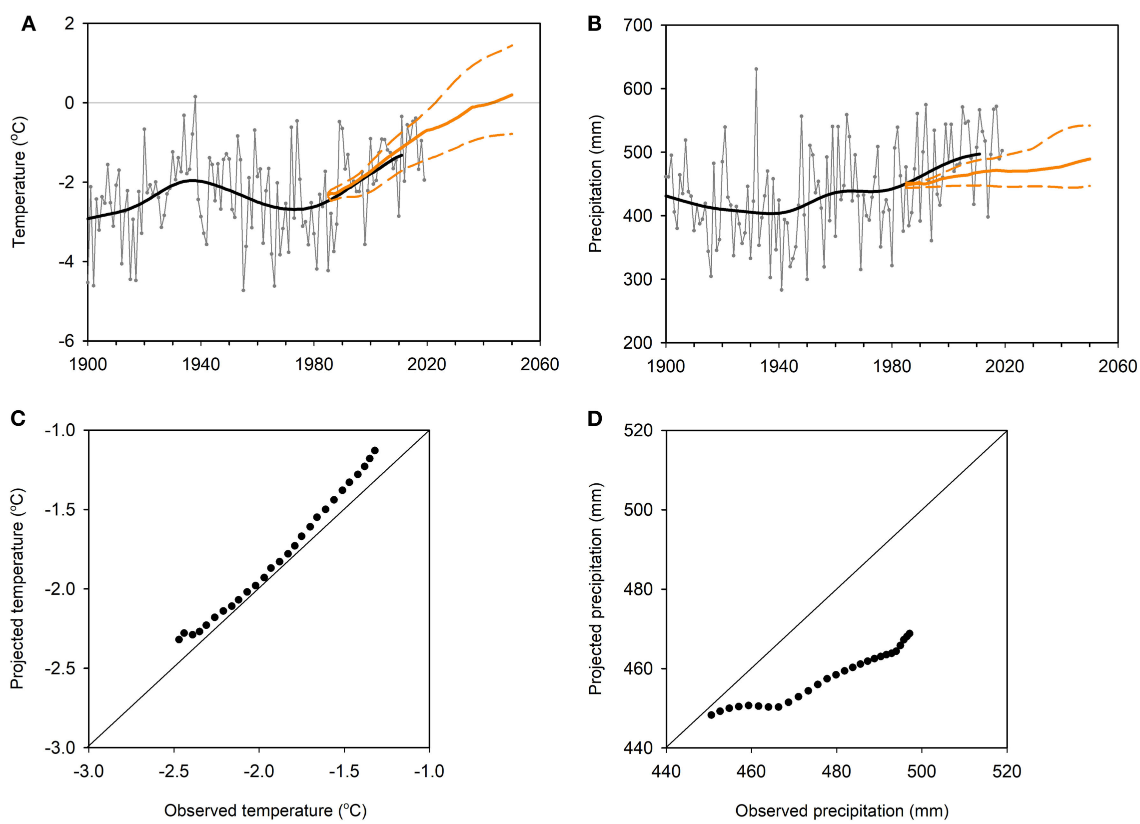

FIGURE 8 | Weather conditions over the reindeer winter pasture area of Finnmarksvidda (**Figure 7**) 1900–2018: observations and projections. **(A)** Mean annual temperature. **(B)** Mean annual precipitation. Observations: data (gray) and low-pass filtered series (black; window ~30 years). Data are averages from 1 × 1 km gridded datasets covering the entire region, based in turn on observations of temperature and precipitation from around 30 meteorological stations within it. Projections (RCP4.5 scenario): median (brown line) and 10 (lower) and 90 (upper) percentiles (dashed brown lines) of ten RCM projections (Hanssen-Bauer et al., 2015, 2017). The percentiles describe the spread of the mean values of all the different models. They illustrate the uncertainty of the mean projections under the RCP4.5 scenario (**Box 3**) not the projected inter-annual variability. **(C,D)** Comparison of observations and projections for median annual temperature and precipitation for the period 1985–2011 [data from **(A,B)**, respectively]. In each case the diagonal lines represent the position of perfect prediction. Expected (projected) and observed data have been plotted on the ordinate and abscissa, respectively, for ease of comparison with **(A,B)**.

precipitation in cold areas but then to decrease where increased temperature causes rain or melting (Hanssen-Bauer et al., 2015, 2017).

Observations: Weather Conditions 1968–2018

Temperature

The mean temperature over the reindeer winter pasture area of Finnmarksvidda during the snow season (October to April, O-A) increased by 2.3°C across the last 50 years, from regression estimates of −10.4°C in 1969 to −8.1°C in 2018 (**Figure 9A**). The average rate of warming was therefore $0.46^{\circ}\text{C} \cdot \text{decade}^{-1}$. The observed increase is slightly less than the median projections for the corresponding period under a medium scenario (2.5–3.1°C; **Table 1**). The pattern of warming has been remarkably consistent across the region: the data from five weather stations spread across 120 km (**Figure 7**) are closely correlated (correlation coefficients of inter-annual variation between the stations range from 0.95 to 0.99; **Figure 9A**). The temperature varied considerably from year to year at every station. The mean annual O-A temperature (all stations combined) deviated from the regression model by, on average, |1.1|°C (range: −2.9 to 2.7°C; **Figure 9B**) which is equivalent to half the linear trend over the entire period 1969–2018. There was also conspicuous decadal variation in temperature: winters in the early 1970s and 1990s were consistently warmer than indicated by the 50-year regression line while the 1980s and late 1990s were consistently colder than indicated by the line (**Figures 9A,B**).

Annual and decadal variability in temperature is connected to variation in atmospheric circulation patterns such as the North Atlantic Oscillation index (NAO; see **Box 3**; Hanssen-Bauer and Førland, 2000; Hanssen-Bauer, 2005). Thus, the annual mean temperature in the reindeer winter pasture area of Finnmarksvidda is strongly correlated with the NAO annual index (**Figure 10**). The NAO seems to influence trends in regional weather conditions over several decades, alternately countering and then amplifying trends related to increases in concentrations of greenhouse gases (Deser et al., 2017). There is still no consensus concerning how global warming may affect the NAO: Rind et al. (2005) have argued that it may lead to more frequent positive values of the NAO. Such an effect would potentially amplify the warming of the reindeer winter range of Finnmarksvidda consistent with the positive correlation between temperature and the NAO index (**Figure 10**). It might also increase precipitation although the correlation between precipitation and the NAO index in this region is quite weak (Hanssen-Bauer, 2005). The effects of more frequent positive values of the NAO on the depth and cover of snow are likely to be complex. Increased temperature and precipitation would potentially result in more snow but only so long as the temperature stayed below 0°C, while warmer temperatures that reduce the duration of the frost season would potentially result in a shorter snow season.

TABLE 1 | Projected change in annual and seasonal 30-year averages of temperature (ΔT°C) and precipitation (ΔR %) over the reindeer winter pasture area of Finnmarksvidda (**Figure 7**) from the reference period 1971–2000 toward the middle of the 21st Century (2031–2060) under the RCP4.5 scenario (**Box 3**).

		ΔT (°C)	ΔR (%)
Annual		+2.5 (+1.3, +4.0)	+9 (0, +17)
Winter	(December–February)	+3.1 (+0.7, +5.8)	+8 (0, +20)
Spring	(March–May)	+2.8 (+0.7, +5.1)	+8 (−3, +12)
Summer	(June–August)	+2.0 (+0.8, +3.4)	+11 (+4, +24)
Autumn	(September–November)	+2.5 (+0.9, +4.2)	+8 (−6, +14)

Results from 10 RCM runs (Hanssen-Bauer et al., 2015, 2017). Data are median (10, 90 percentile).

Start and End of the Frost Season

Consistent with warming, winters are becoming shorter. The onset of the frost season on Finnmarksvidda has occurred progressively later, and the offset of the frost season (i.e., the spring melt) progressively earlier, across the last five decades. The onset of the frost season has delayed by 9.8 days, from a regression estimate of 8th October [day of year (DoY) = 280.9] in 1969 to 18th October (DoY = 290.7) in 2018; the average rate of delay has therefore been 2.0 days · decade^{-1}. The end of the frost season has advanced by 9.3 days, from a regression estimate of 27th May (DoY = 116.9) in 1969 to 6th May (DoY 126.4) in 2018; the average rate of advance has therefore been 1.9 days · decade^{-1} (**Figure 11A**). Both effects have been consistent across the region: the data from five weather stations are closely correlated (correlation coefficients of inter-annual variation between the stations ranges from 0.68 to 0.86 for the start of the frost season and from 0.37 to 0.83 for the end of the frost season; **Figure 11A**). The dates of each, however, varied considerably from year to year at all stations. The date of the start of the frost season deviated from the regression model by, on average, 7.4 days (range: 52 days); corresponding values for the end of the frost season were 7.5 days (range: 44 days; **Figure 11B**).

Thaw Days

The number of days in winter (O-A) with middle ambient temperature above 0°C ('thaw days') increased by 13 (58%) across the last 50 years, from regression estimates of 22 days in 1969 to 35 days in 2018; the average rate of increase was therefore 2.6 days · decade^{-1} (**Figure 12A**). The period October to April counts 212 days (213 in leap years), and 35 thaw days therefore represent 16.5% of the total period. The effect was consistent across the region: the data from five weather stations are closely correlated (correlation coefficients of inter-annual variation between the stations ranges from 0.77 to 0.96; **Figure 12A**). The number of thaw days varied considerably from year to year at all stations. The annual mean deviated from the regression model, on average, by 5.8 days (range: 30 days; **Figure 12B**). The average number and average duration of periods of thawing have increased only slightly across the last 50 years, from regression estimates of 9 in 1969 to 11 in 2018 and from 2.3 to 3.1 days, respectively. Annual values for the

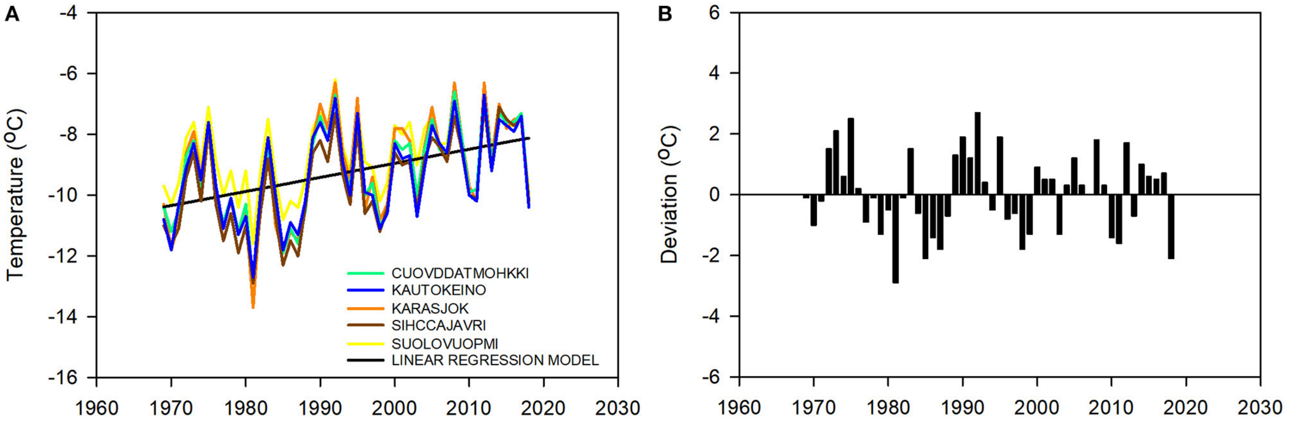

FIGURE 9 | Winter warming. **(A)** Mean annual ambient temperature (October to April, O-A) and linear trend in temperature (°C) over the reindeer winter pasture area of Finnmarksvidda (**Figure 7**), 1969–2018. Data from five weather stations: Cuovddatmohkki, Karasjok, Kautokeino, Sihccajavri and Suolovuopmi (**Figure 7**). The linear regression model (straight black line), O-A(°C)$_{year}$ = [(0.05 · year) – 101.75], $r^2 = 0.21$, $p < 0.001$), is based on data combined from all five stations. **(B)** Annual deviations (°C) from the regression model.

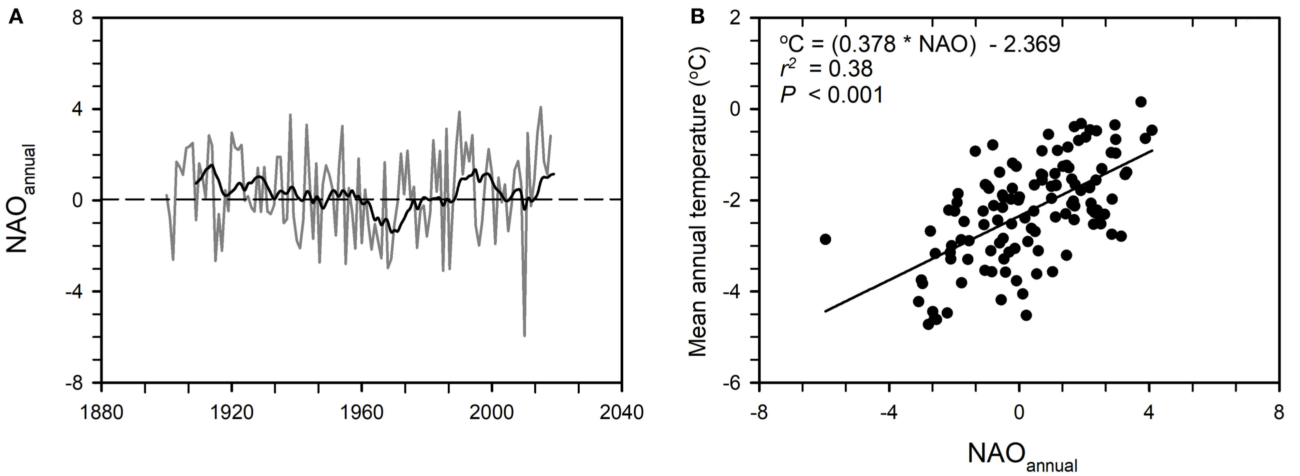

FIGURE 10 | Influence of large-scale climate on local weather. **(A)** Annual values of the North Atlantic Oscillation annual index 1900–2018 (NAO$_{annual}$, gray curve). The trend is indicated by a 10-year running mean (black curve). **(B)** Relationship between NAO$_{annual}$ and the mean annual temperature over the reindeer winter pasture area of Finnmarksvidda (**Figure 7**), 1900–2018. Each point represents one year. Data: Hurrell and National Center for Atmospheric Research Staff (2020), Norwegian Meteorological Institute.

former, in particular, deviate substantially around the 50-year trend (**Figure 13**).

Precipitation

Precipitation in winter (O-A) on Finnmarksvidda increased by 66 mm (52%) across the last 50 years, from a sum of 127 mm in 1969 to 193 mm in 2018 (linear regression estimates; data from six station combined), yielding an average rate of increase of 13.4 mm · decade^{-1}. The observed annual mean deviated, on average, by |13.1|% (range: −36.4 to 44.0%) around the linear trend. In contrast to the previous parameters, the linear rate of increase varied substantially across the region, ranging from 8.6 mm · decade^{-1} at Suolovuopmi in the north to 22.3 mm · decade^{-1} at Sihccajarvi in the south from initial (1969) estimates of 175 and 131 mm, respectively (**Figure 14**). Moreover, a conspicuously wetter-than-average period was evident during the 1990s in the west of the region (Kautokeino and Suolovuopmi) but not in the east (Karasjok and Skogfoss), and there was a conspicuous decrease in the level of variation in precipitation in the east of the region during the decade up to 2018 (Skogfoss; **Figure 14**).

Average Depth of Snow

The average depth of snow in March (the snowiest month) on Finnmarksvidda increased by 14 cm (31%) across the last 50 years, from regression estimates of 45 cm in 1969 to 59 cm in 2018; the average rate of increase was therefore 3 cm · decade^{-1} (**Figure 15B**). This value, however, disguises

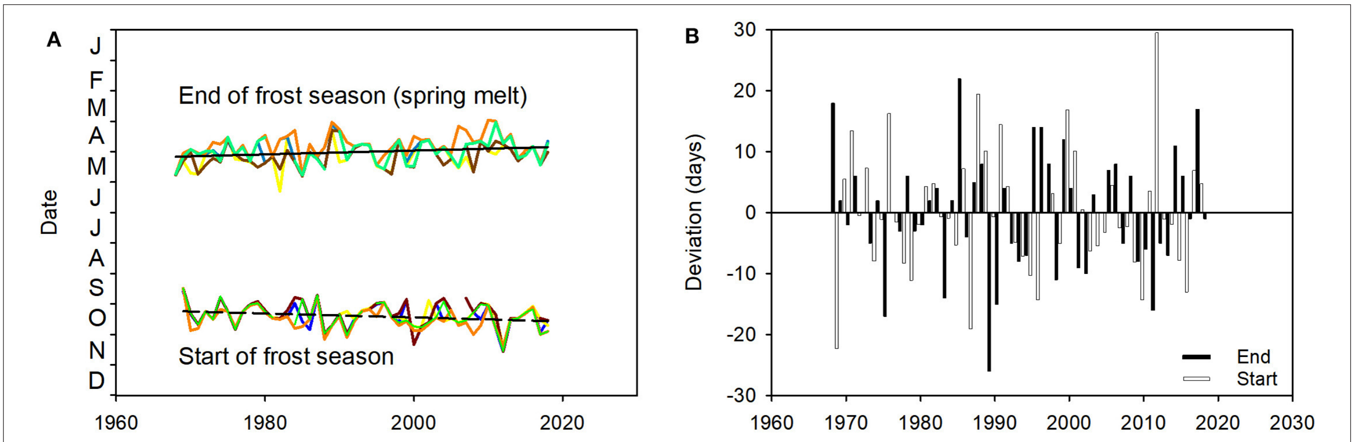

FIGURE 11 | Date of the start of the frost season in autumn and the end of the frost season in spring on the reindeer winter pasture area of Finnmarksvidda (**Figure 7**), 1969–2018. Data from five weather stations: Cuovddatmohkki, Karasjok, Kautokeino, Sihccajavri and Suolovuopmi (**Figure 7**). **(A)** Annual date of start and end, and trends in dates from linear regression models: $\text{Date}_{\text{start}} = [(0.199 \cdot \text{year}) - 110.9]$, $r^2 = 0.08$, $p < 0.05$ (straight dashed line) and $\text{Date}_{\text{end}} = [(-0.188 \cdot \text{year}) + 497.2]$, $r^2 = 0.08$, $p < 0.05$ (straight solid line). **(B)** Annual deviations from the regression models (days; note expanded ordinate scale). For color codes, see **Figure 9**.

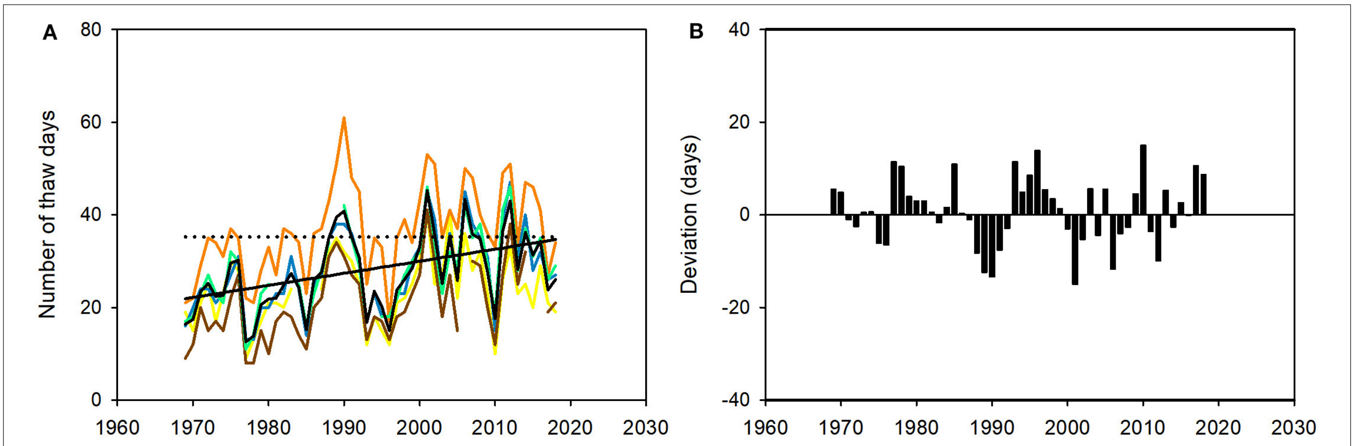

FIGURE 12 | The number of days in winter (October to April, O-A) on the reindeer winter pasture area of Finnmarksvidda (**Figure 7**) with middle ambient temperature >0°C ('thaw days'), 1969–2018. Data from six weather stations: Cuovddatmohkki, Karasjok, Kautokeino, Sihccajavri, Skogfoss and Suolovuopmi (**Figure 7**). **(A)** Annual mean value for all stations combined (black curve) and at each station (colored curves; days), and trend in numbers of days from a linear regression model O-A_{year} thaw days $= [(0.26 \cdot \text{year}) - 491.45]$, $r^2 = 0.22$, $p < 0.01$ (straight black line). The dotted black line shows how the regression estimate for 2018 (35 days) was exceeded by the observed annual average in only 15.2% ($n = 5$) of years before 2001 but in 47.1% ($n = 8$) of years after 2001. **(B)** Annual deviations from the linear models (days). For color codes, see **Figure 9**.

considerable variation in snow depth from year to year at the five weather stations (**Figure 15A**). Annual March depth of snow deviated, on average, by $|6.9|$ cm (range: −25.5 to 18.1 cm or −45.3 to 37.6%) around the linear trend (**Figure 15C**). There was conspicuous decadal variation in snow depth: thus, the 1980s and 1990s were characterised by greater depth of snow than predicted by the regression model, while snow depths in the first decade of the present century were consistently lower than predicted (**Figure 15C**). The pattern and the rate of increase in snow depth also varied across the region. The annual coefficient of variation of snow depth among the five weather stations varied seven-fold, from 4.6 to 31.4%, while the average rate of increase in snow depth ranged from 2 cm · decade^{-1} (Karasjok) to 6 cm · decade^{-1} (Skogfoss; **Figure 15B**).

Number of Days With Snow Cover

There were on average 21 (9.5%) fewer days with snow cover in winter (O-A) on Finnmarksvidda in 2018 ($n = 198$) compared to 1969 ($n = 219$); the average rate of decrease was therefore 4 days · decade^{-1} (**Figure 16A**). There was, however, considerable annual variation at all stations (**Figure 16A**). The observed annual mean deviated, on average, by $|9.5|$ days (range: −31.4 to 19.0 days or −14.5 to 9.2%) around the linear trend (**Figure 16B**).

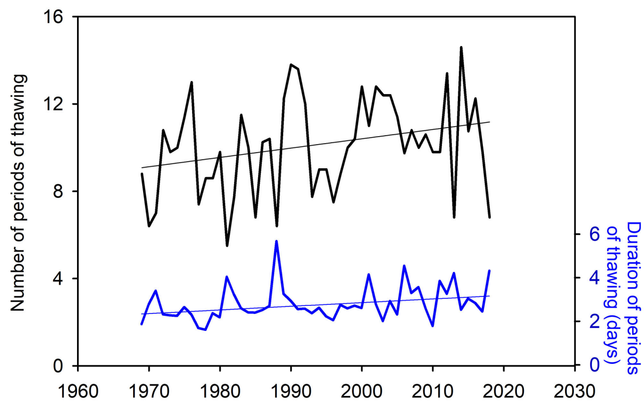

FIGURE 13 | The average number (n) and duration (days) of periods of thawing in winter (October to April, O-A) on the reindeer winter pasture area of Finnmarksvidda (**Figure 7**), 1969–2018. Data combined from five weather stations: Cuovddatmohkki, Karasjok, Kautokeino, Sihccajavri and Suolovuopmi (**Figure 7**). Trend lines derive from linear regression models: Number of $\text{days}_{\text{year}} = [(0.043 \cdot \text{year}) - 74.993]$, $r^2 = 0.08$, $p = 0.05$ and Average $\text{duration}_{\text{year}} = [(0.017 \cdot \text{year}) - 30.695]$, $r^2 = 0.095$, $p < 0.05$.

The climate of the north of Norway is changing and with it, this analysis has shown, weather conditions that influence the level of resources on reindeer pasture there. The dynamic, however, includes another dimension: human intervention can alter the resource base in ways entirely independent of climate change and to which the analysis now turns.

HUMAN INTERVENTION IN AN EXTENSIVE GRAZING SYSTEM

> *Loss of land area is the greatest threat to future viable reindeer husbandry [in Norway today].*
>
> (Government of Norway, 2016, p. 69)

Reindeer husbandry is an extensive form of land use. Approximately 40% (141,000 km^2) of Norway's mainland is designated reindeer pasture (**Box 2**) and within this area Saami herders have—in principle—the right to graze their animals on uncultivated land (*utmark*) irrespective of ownership (below). Herders' right of usufruct (**Box 2**), however, affords them neither exclusive access to land nor protection from the activities of other land users. Conflicts of interest are common. For herders the principle issue is the securing of pasture on which to graze their reindeer. Indeed, the progressive and effectively irreversible loss of grazing land is recognized as the single greatest threat to reindeer husbandry in Norway today (Government of Norway, 2016, p. 69).

Herders lose pasture principally in two ways: physical loss and non-physical loss (Tyler et al., 2007). Physical loss occurs where pasture is either physically destroyed, transformed into another biotope (such as water or agri- or silviculture), or rendered unavailable by the erection of barriers that physically exclude reindeer from it. Non-physical loss occurs either where herders are individually or collectively denied the right to graze pasture that is otherwise available, or where their access to pasture is reduced by disruption of animals' mobility (including obstructing migration routes), or where the value of pasture as a resource is reduced as a result of human activity, the latter manifest as avoidance behavior (below).

Physical Loss of Pasture

Expansion of agriculture was historically the principal cause of loss of prime lowland reindeer pasture in Norway. Ethnic Norwegian (i.e., non-Saami) people moved north and east into remote parts of the country throughout the 18$^{\text{th}}$ and early 19$^{\text{th}}$ Centuries and settled areas that had previously largely been unoccupied save for Saami. Settlement was encouraged by the government through legislation designed to stimulate agriculture by affording farmland legal protection from grazing by reindeer which was mandated by the imposition of substantial fines on transgressors (Hætta et al., 1994; Strøm Bull, 2015). Today, by contrast, the principal physical cause of loss of pasture is construction. Reindeer can graze a field even if they are not supposed to (**Figure 17**) but pasture covered by asphalt, concrete, wood or water leaves them nothing. The effect is absolute and effectively irreversible.

Domestic and commercial building and infrastructure expanded across Norway during the 20$^{\text{th}}$ Century (**Figure 18**). The physical loss of pasture resulting from this, however, was and is small and localized. In 2019 just 365 km^2 or 0.5% of the northernmost county of Troms and Finnmark (74,830 km^2) were classified as built upon (data: Statistics Norway https://www.ssb.no/statbank/table/09594). Agriculture likewise currently represents only small-scale encroachment, albeit on the best land: in 2017 just 331 km^2 or 0.4% of the same area was under cultivation. Altogether 3,544 km^2 or 2.5% of the whole Saami reindeer husbandry area is currently under cultivation (not including forestry; data: Statistics Norway https://www.ssb.no/statbank/table/11506). The most extensive components of infrastructure, in terms of area covered, are technical installations associated with transport (e.g., roads, airports, energy and water facilities); the most rapidly increasing component has been building associated with industry and other forms of commercial activity (**Figure 19**). Recreational cabins/huts (Norwegian: *hytter*) and their grounds, though small in extent (occupying in 2017 just 199 km^2 or 0.1% of the Saami reindeer husbandry area), are a significant feature of encroachment because they are invariably situated in the mountains and along the coastal strip where reindeer graze. On average, 1,450 (range 1,231–2,135) huts have been built in the Saami reindeer husbandry area annually during the last 20 years and in 2017 there were some 135,000 huts, almost 1 per km^2, there (Data: 1998–2017 from Statistics Norway https://www.ssb.no/statbank/table/06952).

Non-physical Loss of Pasture

Evolution of the Legal Right to Graze

Saami reindeer herders in Norway, like indigenous pastoralists throughout the world, generally do not own the land they use. The *utmark* on which they graze their animals—and cut timber, collect fuel, gather berries, catch fish and hunt—is generally

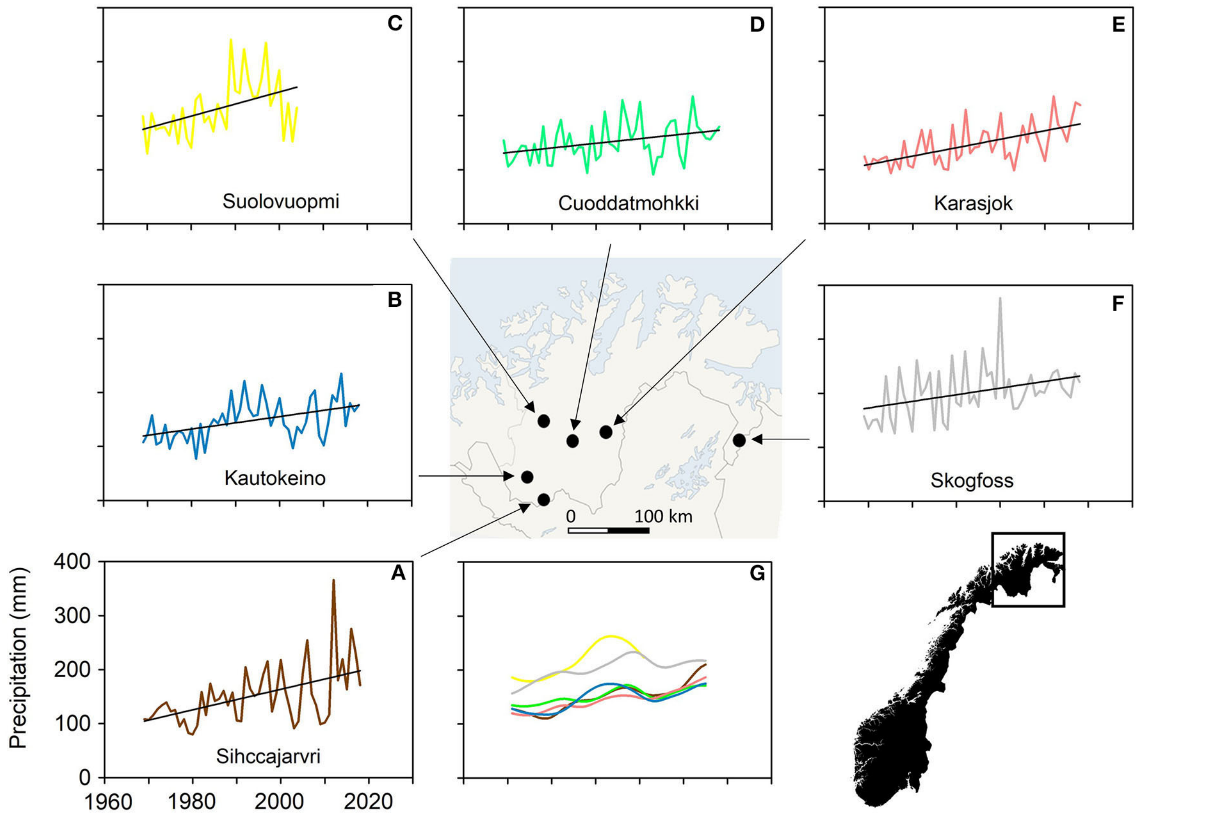

FIGURE 14 | Total precipitation in winter (October to April, O-A; mm) on the reindeer winter pasture area of Finnmarksvidda (**Figure 7**), 1969–2018. **(A–F)** Raw data from six weather stations: Cuovddatmohkki, Karasjok, Kautokeino, Sihccajavri, Skogfoss and Suolovuopmi (**Figure 7**). **(G)** Low-pass filtered data (window ~30 years: the first and last three years in the time series from each station are excluded). Precipitation increased at all stations over the last 50 years. Linear regression coefficients (mm · year^{-1}) are Cuovddatmohkki 0.860, $p = 0.1$ *NS*; Karasjok 1.561, $p < 0.001$; Kautokeino 1.157, $p < 0.001$; Sihccajavri 1.190, $p < 0.001$; Skogfoss 1.226, $p < 0.01$; Suolovuopmi 2.233, $p < 0.01$. The level and pattern of change in precipitation was generally uniform across the region but with some exceptions. Skogfoss and Suolovuopmi, for instance, were consistently wetter than all other stations **(G)**.

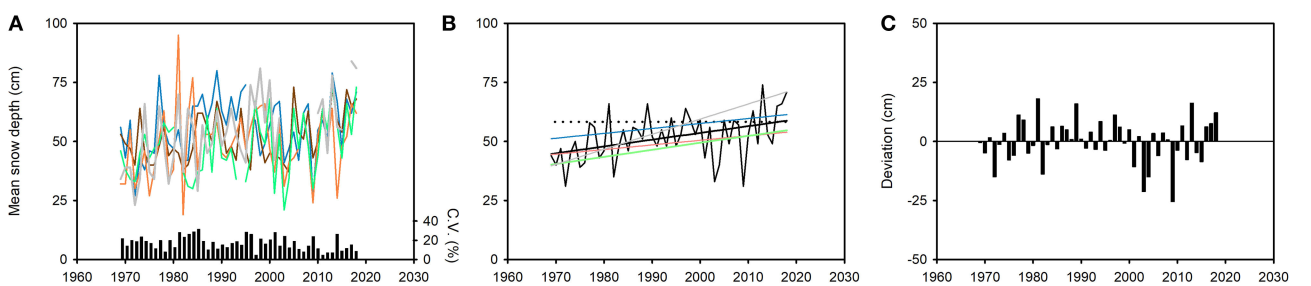

FIGURE 15 | Average depth of snow in March (the snowiest month) on the reindeer winter pasture area of Finnmarksvidda (**Figure 7**), 1969–2018. Data from five weather stations: Cuovddatmohkki, Karasjok, Kautokeino, Sihccajavri and Skogfoss (**Figure 7**). **(A)** Annual mean values at each station (cm) and annual coefficient of variation (C.V.) in mean depth across all stations (%). **(B)** Trends in snow depth from linear regression models. The model for the combined dataset (black curve) is Average depth (cm)$_{year}$ = [(0.288 · year) – 522.45], $r^2 = 0.18$, $p < 0.01$(solid black line). The dotted black line shows how the regression estimate for 2018 (58.8 cm) was exceeded by the observed annual average only six times prior to 2011. Regression lines (but not data) for each station (excepting the regression line for Sihccajarvi which is indistinguishable from the line for the combined data set). **(C)** Annual deviations from the regression model for the combined dataset (cm). For color codes, see **Figure 9**; gray: Skogfoss.

owned by the State or by corporate or private non-pastoralists. Historically, however, it served as *de facto* commons. The right of herders to use such land derived from unwritten customary law and subsequently achieved legal recognition on the principle that rights accrue where there has been 'use since time immemorial' (Norwegian: *alders tids bruk*; Ravna, 2010a; Strøm Bull, 2015).

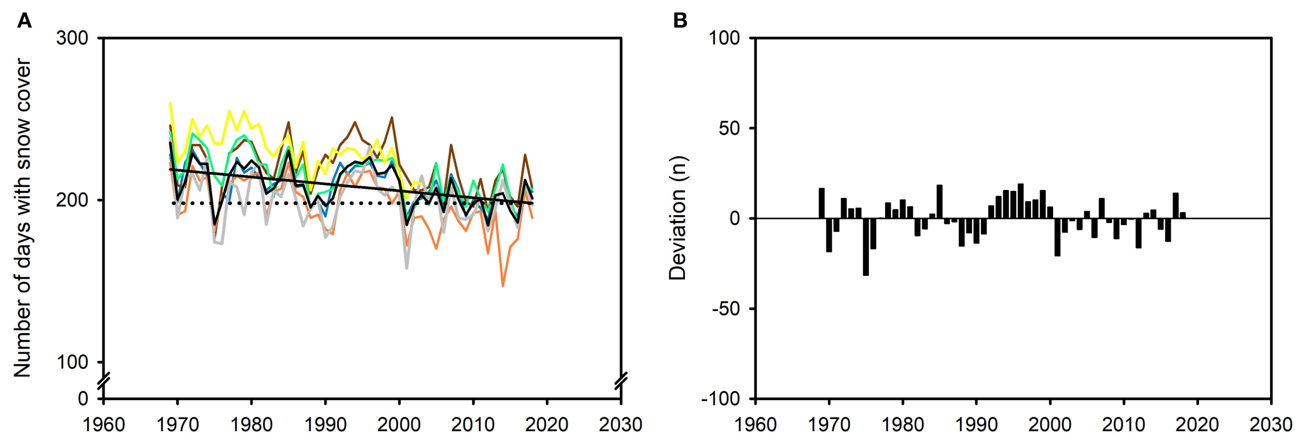

FIGURE 16 | Number of days with snow cover in winter (October to April, O-A) on the reindeer winter pasture area of Finnmarksvidda (**Figure 7**), 1969–2018. Data from six weather stations: Cuovddatmohkki, Karasjok, Kautokeino, Sihccajavri, Skogfoss and Suolovuopmi (**Figure 7**). **(A)** Annual mean value for all stations (black curve) and for at each station (colored curves; days) and the trend in number of days derived from a linear regression model (data combined for all stations): Number of $\text{days}_{\text{year}} = [(0.43 \cdot \text{year}) + 1058.5]$, $r^2 = 0.23$, $p < 0.001$ (black line). The average number of days with snow cover exceeded the regression value for 2018 (198 days) in 29 (91%) of the first 32 years of the series (1969–2000) but in only 10 (56%) of the last 18 years (2001–2018; dotted line). **(B)** Annual deviations from the model for the combined dataset (*n*). For color codes, see **Figure 9**; gray: Skogfoss.

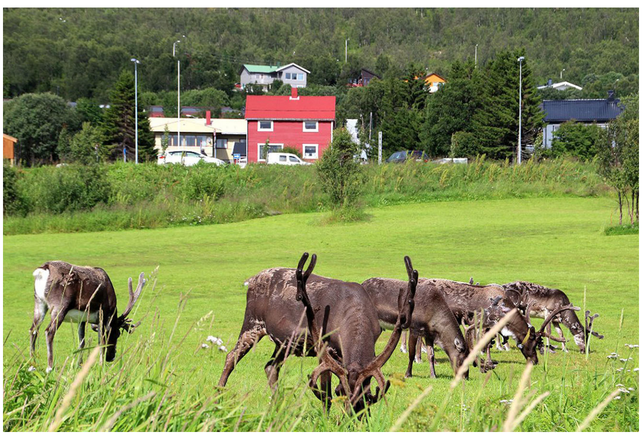

FIGURE 17 | Illegal grazing: herders are not allowed by law to graze reindeer on actively cultivated ground (Government of Norway, 2007, §19). Are these male reindeer, enjoying a lawn on Kvaløysletta just outside Tromsø, Norway, encroaching on cultivated ground or has cultivation encroached on traditional reindeer pasture? Photograph: Bjørn Lockertsen.

The right to graze *utmark*, formally codified in the Lapp Codicil of 1751 (Pedersen, 1987; Hætta et al., 1994; Mazzullo, 2009; Ravna, 2010b) seems generally to have been accepted until the late 19th Century when, however, it was challenged on several grounds. (Note: 'Lapp' was a then contemporary word for 'Saami').

In 1889 Professor Yngvar Nielsen confronted the conventional view—that Norwegians encroached on land to which the Saami, as the original inhabitants, had precedence—with evidence that the former were in fact the original occupiers. He argued, in particular, that Saami people did not settle the area around the town of Røros, in southern part of what is today the reindeer herding area of Norway (**Figure 3**), until after it had been occupied by Norwegians in the 18th Century. From this it followed that Saami herders encroached on Norwegian farm and hill pasture rather than the other way around. A Lapp Commission, convened later that year to investigate Professor Nielsen's claim, concurred and, in doing so, legitimized an interpretation which constrained Saami grazing rights for the next 100 years (Strøm Bull, 2015).

Professor Nielsen's historical appraisal of patterns of settlement resulted in a fundamental challenge to herders' use of *utmark*. Thus, in 1926 the view was advanced that the Saami right of usufruct was an instance not of 'use since time immemorial' but of 'tolerated use' (Norwegian: *tålt bruk*). It followed that their use was subject to statutory legislation on the basis that a right conferred by the State might equally be withdrawn at any time by the State (Strøm Bull, 2015). This interpretation was refined by a judgement in 1955 that herders' rights of hunting and fishing applied only to State commons and not to private land. Private landowners desiring to forbid Saami herders access to their land prevailed before the Land Consolidation Court and subsequently at the Court of Appeal before, in 1968, both the decisions were reversed by the Norwegian Supreme Court. The Supreme Court ruled that Saami reindeer herders' historic use of land might on occasion be so grounded in custom that it could not summarily be equated with usufruct or any common right of access. In the opinion of the court such use represented an independent legal basis from which, furthermore, stemmed the right of compensation for expropriation (Strøm Bull, 2015).

It remained unclear, however, exactly to which areas and to what land the 1968 ruling applied. In a series of cases, lower courts attached decisive weight to descriptions of land use drawn from the report of the Lapp Commission of

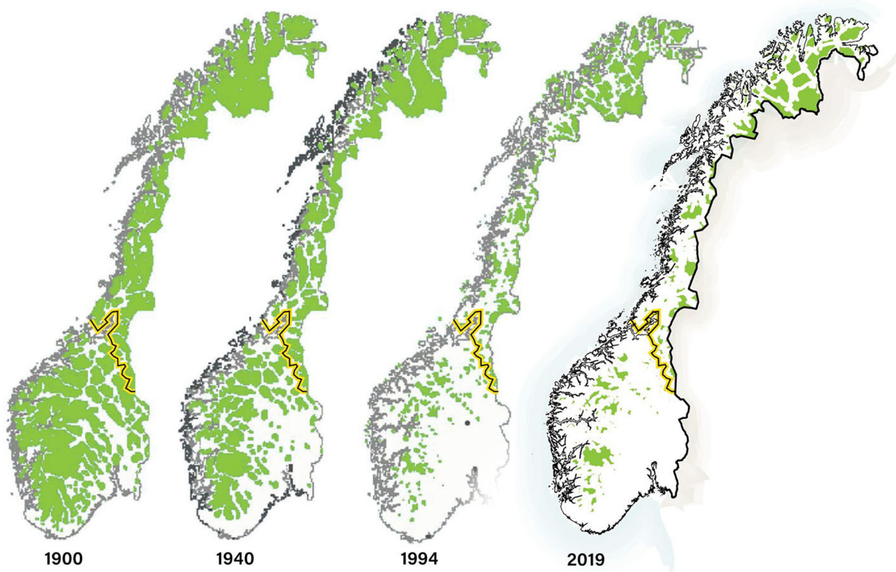

FIGURE 18 | Loss of habitat: distribution of areas of Norway >5 km from any infrastructure (green shading) 1900–2019. The yellow line marks the southern boundary of the Saami reindeer husbandry area (see **Figure 3**). Sources: Nellemann et al. (2003), Norwegian Mapping Authority.

1889. This encouraged private landowners to claim that Saami herders had no right to herd reindeer outside areas specifically mentioned in the Commission's report. Their challenge, brought to court in 1995, was indirectly supported by the Royal Ministry of Agriculture which, ignoring the Supreme Court's ruling, based the 1978 Reindeer Herding Act on the premise that the right to engage in reindeer husbandry was governed exclusively by statutory regulation. The Ministry's interpretation was subsequently reversed by an amendment to the Act passed in 1996. However, it was not until 2001—exactly 250 years after the Lapp Codicil—that the Supreme Court confirmed the use of *utmark* for pasturing reindeer to be an independent right based on use since time immemorial and independent, therefore, of the provisions of the 1978 Act. On this occasion, the court explicitly recognized the inherent difficulty of demonstrating prolonged and continuous use of land. It therefore specified that weight should always be given to the 'nature of the right'—a reference to the itinerant character of land use which is the hallmark of reindeer husbandry—and that lengthy interruption of the use of a particular area was insufficient to hinder the acquisition of rights of use (Strøm Bull, 2015).

Professor Nielsen's 1889 report thus spawned uncertainty and controversy which reverberated through the courts for more than a century and which continues to reverberate in the public discourse about Saami reindeer pastoralism to the present day (e.g., Larsen, 2019). It is dismaying therefore to note that his conclusion regarding the sequence of occupation of land around Røros, and hence his allegation that Saami reindeer herders encroached on land already occupied by Norwegian peasant farmers, was incorrect. In 1799 the Revd. Thomas Malthus FRS (1766–1834), the English priest and scholar best known today for his theory of population growth, travelled through the area that Nielsen explored a century later. He recorded how Mr. Knoph, the Director of the Røros Copper Words, informed him that Saami people 'had inhabited these mountains before Røros was known.' This, and Malthus' own observations of Saami reindeer herders there, only came to light when the latter's diaries were published in 1966 (James, 1966, p. 189–195). Knoph's observations regarding the antiquity of the Saami presence in the area have subsequently been corroborated by evidence of Saami heritage throughout the region (Strøm Bull, 2015). The situation around Røros, moreover, was not unique in this regard. Throughout the country Norwegians settled areas already used by Saami reindeer herders. Thus, the valley of Dividalen in Troms and Finnmark in the north was

> '*… populated … late. The innermost farm … was first cleared in 1844-45 … The settlers' conquest of these areas was of major importance for the use of the mountain [pastures] … Norwegian settlements restricted … Saami traditional use* [Norwegian: 'hevd'] *of the land and obstructed reindeer husbandry … Saami dwelling places were occupied and herders were obliged to shift their migration routes. … The State largely supported the [settlers'] claims [to the land] …*' Kalstad (1974, p. 101).

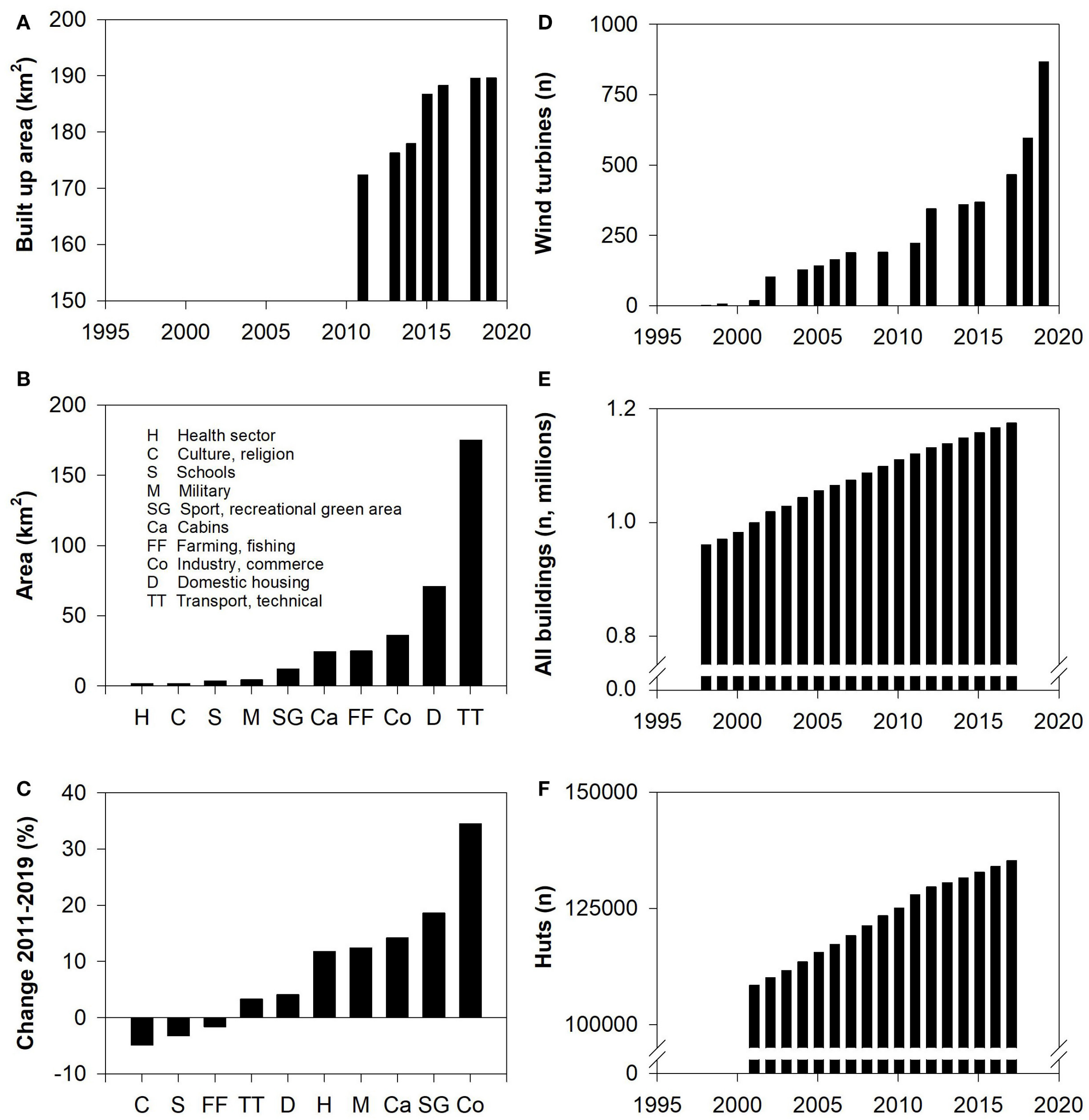

FIGURE 19 | Expansion of infrastructure since 1998 across the Saami reindeer husbandry area. **(A)** Total area of infrastructure (km^2) according to the categories shown in **(B)**. **(B)** Area of infrastructure (km^2) in 2019 by category. **(C)** Proportional change in the area of infrastructure (km^2) from 2011 to 2019 by category (%). **(D)** Number of wind turbines. **(E)** Number of buildings. **(F)** Number of recreational huts and summer houses (Norwegian: *hytter og fritidsbolig*). **(A–C)** Data for the Troms, East and West Finnmark husbandry areas (**Figure 3**); **(D–F)** data for the entire the Saami reindeer husbandry area. Sources: All data except **(D)** Statistics Norway; **(D)** Water Resources and Energy Directorate (NVE).

Legal Constraints on Grazing

Withdrawal of the Right to Graze

> *'Reindeer husbandry ... has been in turmoil since the border was closed in 1852.'*
>
> (Hætta et al., 1994, p. 23).

By far the most extensive loss of reindeer pasture in Norway occurred and occurs through the withdrawal of herders' right of access to land owing to the closure of international borders and to the reallocation of land for other purposes.

International Borders. Long distance movement of large ungulates across rangeland is a ubiquitous and defining feature of extensive grazing systems. In nomadic systems, herds and herders move continuously, opportunistically seeking transient pasture resources along paths that may vary substantially from year to year. In transhumant systems they move between established points that are likely to be regular and of ancient pedigree (Blench, 2000). Reindeer pastoralism in Norway is largely transhumant: Saami herders and their herds normally migrate between discrete summer and winter pastures with the former usually, although not invariably, at the coast and the latter usually, although not invariably, at higher elevation inland (**Box 2**). The animals follow an ecological imperative: they track changing snow conditions in winter and the phenological progression of forage plants across spring and summer just like their wild conspecifics (Skogland, 1984, 1989; Fancy et al., 1989): herders, of course, move with them.

Historically, reindeer herders in Fennoscandia enjoyed freedom of passage across the jurisdictionally unchartered mountains, forests and taiga of the northern landscape. This situation lasted until the 18th and 19th Centuries when borders demarcating the then kingdoms of Denmark-Norway, Sweden-Finland and subsequently Russia-Finland (now the independent countries of Norway, Sweden, Finland and the Russian Federation) were extended across the region (Kirchner, 2020).

Border with Sweden-Finland. The Commission responsible for drawing up the border between northern Norway and northern Sweden-Finland in 1751 (**Figure 20A**) accepted that a closed border would disrupt established patterns of grazing including the seasonal migration of reindeer across the border. It would affect Saami herders in Sweden-Finland who moved west over the mountain divide into Norway in spring before returning east to the low-lying forests of Sweden in autumn and Norwegian Saami herders who moved the other way (**Figure 3**). The Commission therefore proposed that reindeer herders from both countries should be permitted to cross the border with their animals according to customary practice. Herders' rights of passage across the border were secured through the medium of an Appendix (the 'Lapp Codicil') to the Treaty of Strømstad of 1751:

> *'Recognizing that the Saami require [pasture in] both the lands of the realm, they shall be allowed to move with their herds of reindeer across the border into the other kingdom in autumn and spring according to ancient custom. And there, as before, … they shall be allowed to use the land … to sustain their animals and themselves, and must be kindly received, protected and helped to justice just like [all] subordinates of the country [they have entered]'* (Government of Norway, 2015, §10).

The text of the Codicil, moreover, specified that the document carried the same legal weight ('*skal … være af samme Kraft*') as the Treaty itself (Government of Norway, 2015).

Freedom of passage, however, did not entail free use of pasture on each side of the border. The Codicil specified that:

> *'Swedish Lapps who move across the border onto Norwegian ground with their [reindeer shall] pay a ground rent for every 20 animals, … large and small of both sexes, except for calves born in the same spring, one Danish shilling or one Swedish styver, in copper coin, not more …'*

while Norwegian Saami ('Lapps') traveling in the opposite direction were to pay exactly twice as much (Government of Norway, 2015, §13–14). These fees still apply but, given that they are charged at the original rate, uncorrected for 250 years' inflation, the charge is minimal (Øyvind Ravna, personal communication, 8 February 2020).

Neither the Commissioners' appreciation of the function and significance of transhumance nor the legal obligation specified by the Lapp Codicil were sufficient, however, to protect herders' right of movement and cross-border grazing from developments in the organization of, and the relationships between, neighboring countries (below).

Border with Russia. In 1826 (effective from 1827; Gabrielsen, 2009) the border between Norway and Russia was closed with the stated aim of preventing disputes of the kind that arose in the absence of clarity over its exact position ('… *Grund heraf villet forebygge de Tvistigheter, som hidtil have kunne opstaae, paa Grund af, at der savnedes en nøiaktig Grændsebestemmelse imellom Norge og Russland* …' Hætta et al., 1994, p. 14). Then, in 1852, the border with Finland, which Sweden had ceded to Russia in 1809, was closed following Russian refusal to be bound by the Treaty of Strømstad to which she was not a signatory. Thus, at two strokes of the administrative pen reindeer herders in Finnmark lost access to half their traditional winter pasture (Hætta et al., 1994). Not surprisingly, reindeer continued to cross the border and to use winter pasture in Russia and Finland as they were accustomed to do and, equally not surprisingly, measures were instituted to prevent this, including the appointment of bailiffs whose task was to enforce the new legislation. For 7 years (1826–1833) Johan Henrik Cappelen served as bailiff responsible for collecting fines from Norwegian herders whose animals strayed across the border. The fine was set at one specie dollar (*spesidaler*) for each 50 reindeer that crossed. What proportion of the money ever reached the State coffers is unknown but Cappelen's 'luxurious lifestyle and exuberant extravagance' (*råflotte levevis og overmodige utskeielser*) suggested that it was probably not large (Gabrielsen, 2009).

The threat of fines did not, however, stop herders moving animals across the borders. Herders from Varanger in northern Norway continued to use pasture in Russia, traveling as far east as the River Titovka and sometimes beyond it onto the Kola Peninsula (**Figure 20B**; Leinonen, 2007; Odd Erling Smuk, personal communication, 5 February 2020). The Russians had no effective border controls and the practice of grazing animals in Russia in winter continued until 1918 when civil war broke out in Finland:

> *"… war [reached] Petsamo. The hospital in Kirkenes filled with casualties. … it was no longer safe to graze reindeer in the Petsamo region. … [the now independent country of] Finland closed the [formerly Russian] border … and declared that they would slaughter 10% of Norwegian reindeer that entered the Petsamo area [which it now controlled]. Actually, they slaughtered all they could and considerable business activity linked to this developed there as a result. In the spring of 1918 my great-grandfather and grandfather removed [with their herd from Petsamo] to Bugøynes where they stayed until after calving [in May]. Then, around St. Hans's Day [24th June], when the rivers had fallen, they moved [west] onto the Varanger Peninsula. In this way they saved most of their reindeer. Many of my relatives on the other hand lost many reindeer—some lost all: the animals became war food [for soldiers] in Russia."* (Odd Erling Smuk, personal communication, 6 February 2020).

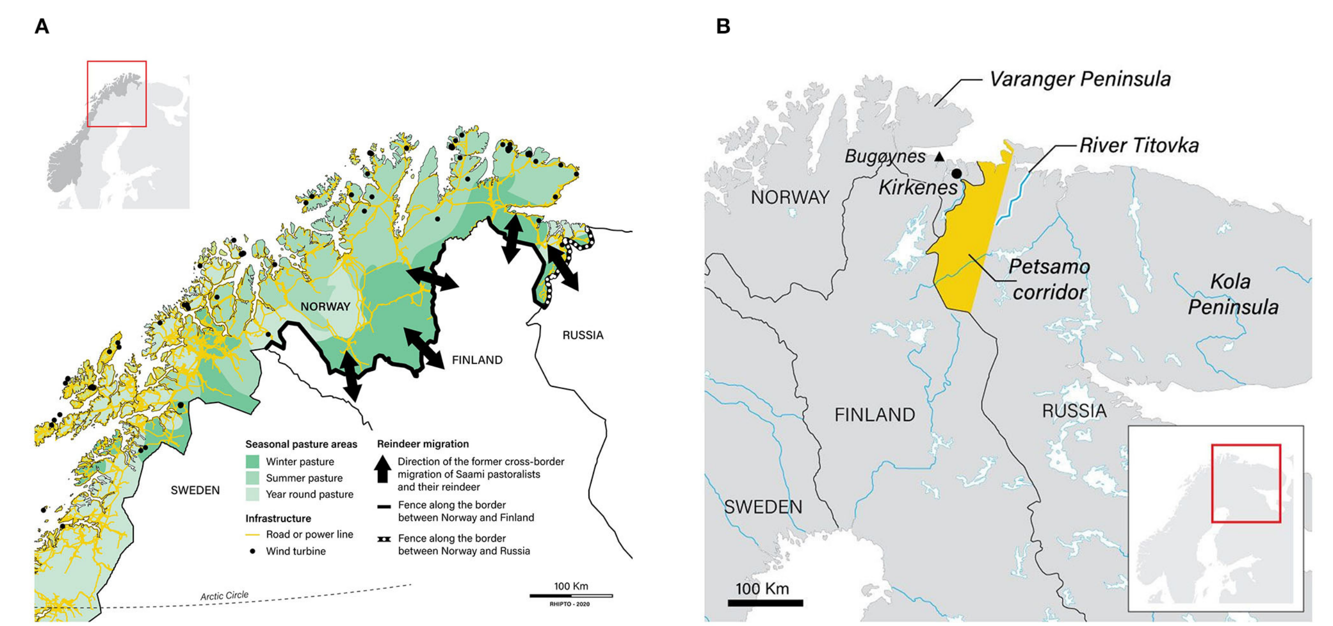

FIGURE 20 | Legal constraints and infrastructure reduce land available for pastoralism. **(A)** Map showing fences (thick lines) built along the border between Norway and Russia (fence 200 km in length) and between Norway and Finland (fence 637 km in length) to prevent cross-border grazing by domesticated reindeer. Heavy black arrows indicate the direction of seasonal migration of reindeer before the borders were closed. The map also shows infrastructure (roads and wind turbines) on seasonal reindeer pasture in northern Norway. Infrastructure and related features that substantially reduce the area of reindeer pasture not shown here include agricultural land, airports, hydro-electricity plant (including flooded ground), industrial plant, military training areas, mines and recreational facilities including private huts, ski fields and walking-, dog-driving, ski- and snowmobile-trails. **(B)** Map showing places mentioned in the text regarding the consequences for reindeer husbandry of the closure of the border with Russia. Sources: Roto (2015) and Government of Norway (2016), Norwegian Mapping Authority.

Following WWII and area known as the 'Petsamo corridor' (**Figure 20B**), which had been ceded by Russia to Finland under the terms of Treaty of Tartu in1920, was returned to the U.S.S.R. (as Russia had now become). In 1949 Norway and the U.S.S.R. agreed their mutual intention of returning to their country of origin any reindeer that wandered across the border. The reality, however, was quite otherwise. Cold War passport controls and visa restrictions prevented Norwegian Saami herders from retrieving stray animals (Hætta et al., 1994). (The problem was one-sided: the Russian side of the border was heavily militarized and there were therefore no reindeer there to stray the other way.) The solution was to prevent the movement of animals and in 1961 construction commenced on a reindeer-proof fence that ultimately stretched 200 km along the Norwegian side of the border all the way south to Finland (Hætta et al., 1994). Work on the fence progressed only slowly. Animals continued to stray and, in 2010, Russian frustration led to a meeting of no less than three Norwegian Government departments (the Ministries of Agriculture and Food, Foreign Affairs and the Environment) to expedite construction (Lien, 2010). The fence was finally completed in 2018 (Directorate of Agriculture, 2019).

Border with Finland. The emergence of Finland as an independent country in 1917 necessitated re-negotiation of the agreement of 1852 whereby the border between the then kingdoms of Norway-Sweden and Russia-Finland had been closed to the passage of reindeer. A convention negotiated in 1922 set out principles for reducing cross-border grazing: it specified the duty of herders to prevent it, the rates of fines, confiscation and slaughter of reindeer which were caught on the wrong side of the border, and the reimbursement to the State of the costs of implementing such measures. The regulations proved ineffective and a new convention, signed in 1935, agreed the erection of 390 km of reindeer-proof fencing along the border, the cost of which was to be divided equally between the two countries. This seems, however, never to have been implemented (Hætta et al., 1994). The situation was aggravated during WWII. Norwegian Saami herders accused Finnish herders of crossing the border and stealing reindeer while Finns, assisted by the German occupation forces in Norway, presented the Norwegian authorities with successive demands for compensation for Finnish reindeer lost—presumably claimed stolen—on the Norwegian side of the border. A third convention on the prevention of cross-border grazing negotiated in 1948 was followed by a fourth, in 1952 (subsequently revised in 1962, 1981, and 2017), which resulted in the erection of 637 km of fencing along of the border (Hætta et al., 1994; Government of Norway, 2016, 2017, p. 26). Thus, the chronology of the judicialization of reindeer husbandry (i.e., the introduction of, and reliance on, judicial means for addressing predicaments and policy questions) at the border between Norway and Finland had three principle milestones each almost exactly 100 years apart: the border was created by the Treaty of Strømstad in 1751 was legally closed in

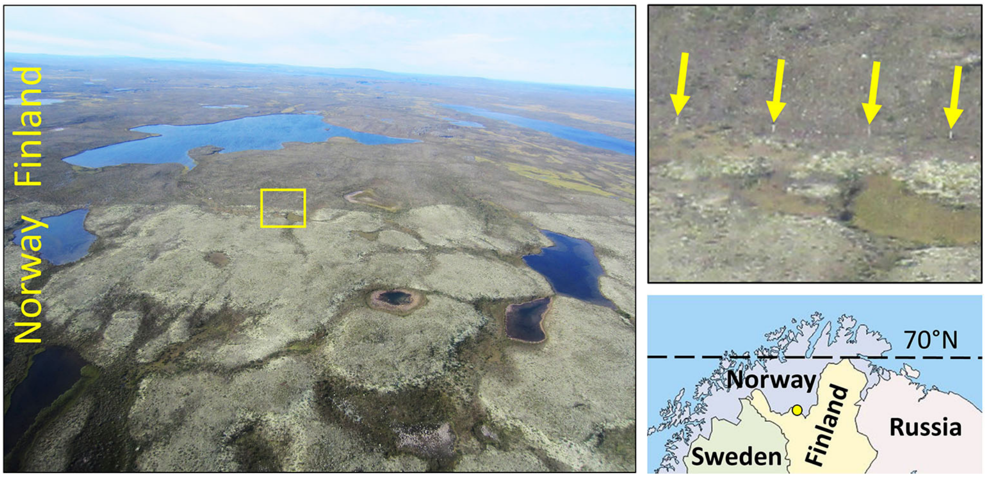

FIGURE 21 | Aerial photograph looking from north to south across the Norway-Finland border on Finnmarksvidda (site indicated by a yellow dot on the location map). The border is evident as a line of change in the color of the ground running horizontally across the middle of the picture. The pale green color of the foreground (Norway) reflects the presence of a continuous mat of terricolous lichens; the brown color in the upper half of the picture (Finland) indicates the absence of lichens, the brown color being due to tundra plants (creeping shrubs, graminoids and mosses). Four posts of the fence erected to prevent the movement of reindeer either way across the border are visible (yellow arrows) in an insert corresponding to the yellow square in the main picture. The lichen mats on the Finnish side of the border have been destroyed by reindeer trampling them in summer when they are dry and therefore brittle. This in turn is a result of the animals having been prevented by the fence from leaving the area and moving to their traditional summer pastures near the coast of Norway. Photograph (21st August 2013): Bernt Johansen.

1852 and was physically closed in 1952. The path between these was flooded by buckets of ink drawn up from a well of legal argument and diplomatic negotiation.

Disrupting migration, whether by imposing a legal obligation on herders to prevent the passage of their animals or by erecting hundreds of kilometers of animal-proof fencing across the route (like the border fences in the present case or veterinary cordon fences in Africa [above]), is obviously a major intervention in the natural function of any extensive grazing system. The consequences of the closure of the border for reindeer husbandry in northern Norway and Finland have been conspicuous and profound:

> *'Reindeer husbandry has been turmoil at the border since 1852, when it was closed, and up to the present day. … the border conventions … have influenced pasture utilization and the pattern of husbandry, and [consequently] … the central authorities have erected an expensive fence system along the border'* (Hætta et al., 1994, p. 23).
>
> *'Reindeer herding has been greatly affected by closure of national borders to cross-border herding migration and [the resulting] foundation of the herding co-operative system … during the past decades. … these have greatly modified traditional pastoralism'* (Markkula et al., 2019).
>
> *'… the closure of the [Finnish]-Norwegian border in 1852 revolutionized old nomadic Saami reindeer husbandry [by] preventing or shortening seasonal migrations'* (Jaakkola, 2014).

The immediate consequence of border closure was that Norwegian Saami herders in Finnmark lost access to approximately half their traditional winter pasture, which was in Finland, while Finnish Saami herders lost access to all their summer pasture in Norway. This led to conspicuous transformation of the habitat, particularly in Finland, and of the structure, organization and pattern of herding on both sides of the border.

Reindeer winter pastures typically include extensive mats of terricolous lichens (e.g., *Cetraria* spp. and *Cladonia* spp.) which, unusually among ruminants, are highly digestible in reindeer (Salgado-Flores et al., 2016) and often comprise a substantial part of the animals' winter diet (Storeheier et al., 2002 and references therein). These lichens are soft and pliant when wet but brittle, easily fragmented and rapidly eliminated by trampling when dry (Crittenden, 2000). The border fence prevented Finnish reindeer from leaving their winter pasture with the result that they trampled on the lichens in summer, when they were dry and brittle, and gradually destroyed them. The effect is evident at the border today as a stark line of demarcation owing to the presence of lichens on the Norwegian side and their absence on the Finnish side (**Figure 21**; see also Väre et al., 1996).

The closing and subsequent fencing of the border caused two major transformations in reindeer pastoralism in northern Finland. First, transhumance was replaced in the 1890s by the development of an intensive herding system in which animals organized within cooperatives were grazed all year round within defined, ultimately fenced, areas. Depletion of the range from the late 1960s, due in part to the trampling of lichens (above), however, led to intensive herding being replaced by an extensive system. In this system animals range freely within the same fenced areas throughout summer but are gathered and held in feeding corrals, where they are provided with concentrates, for several months in winter (Helle and Jaakkola, 2008; Jaakkola, 2014; Turunen and Vuojala–Magga, 2014).

Unlike in Finland, transhumance persists in Norway but the closure of the border created a series of problems for herders there. Topography is crucial to reindeer pastoralism because local relief influences the physical characteristics of the snowpack which is a major determinant of the availability of forage for reindeer in winter (Skogland, 1978; Eira et al., 2018). Loss of access to areas of favorable terrain across the border in Finland has had two principal effects. First, it has resulted in heavier grazing pressure. Second, it has reduced the options available to herders for adjusting the pattern of grazing in response to changes in snow conditions during winter. A Saami reindeer herder from the Varanger area, summarized the situation thus:

> *"We used to be able to move out of the forest and onto the high ground in Finland when necessary but we cannot do that now because the border is closed. Nowadays the way the ground is used is sometimes all wrong. People stay too long in one place and even use winter areas in summer. There are now no places we can set aside for a year or more to guarantee us good grazing in another year. We know this but what can we do? Where can we go? Some herders feed concentrates. Others argue. Herds mix and have to be separated. It is all very difficult"* (Inger Anita Smuk, personal communication, 12 February 2020).

Border with Sweden. The legal constraints on cross-border grazing between Norway and Sweden differ fundamentally from those at the borders with Finland and Russia: this border has never been closed. The Lapp Codicil of 1751, which secures the right of herders and their animals to cross the border according to ancient custom (above), has never been revoked and therefore remains in force. However, the reciprocal rights of cross-border grazing intended and guaranteed by the Codicil have nevertheless been progressively eroded.

In addition to securing their right to cross the border, the Lapp Codicil specified a series of duties and responsibilities for transhumant herders. These included a requirement to report the numbers and the individual ownership of animals, and to adhere to itemized limits regarding the use by herders of one country of pasture and other resources in the other (Government of Norway, 2015, §§15–21). From these few rules there subsequently developed more elaborate and comprehensive regulations for reindeer pastoralism in the two countries of (from 1814 to 1905) the joint kingdom. Cross-border grazing was regulated by the Common Lapp Law (*Felleslappeloven*) which passed into law in 1883 after no less than 40 years' enquiry and planning. This law included a novel provision whereby land could, where necessary, be closed to reindeer specifically to protect the interests of farming and forestry (Hætta et al., 1994). Negotiations leading up to the dissolution of the union of the joint kingdom of Sweden and Norway in 1905 afforded the Norwegian authorities an opportunity to tighten this constraint by exerting pressure on the Swedes to reduce the extent of grazing by Swedish Saami on the Norwegian side. Reindeer Grazing Conventions were negotiated and agreed between the now independent countries in 1919 and 1949. The area of summer pasture in Norway available to the four northernmost Swedish herding co-operatives alone was reduced by 53%, from 17,000 to 8,053 km^2 (Koch and Miggelbrink, 2011). The dissatisfaction that this caused festered but the authorities remained resolute. In 1968 a claim by Swedish Saami for compensation for pasture lost in Norway following the construction of a hydroelectricity plant at Lake Alte was rejected on the grounds that under the terms of the 1919 convention members of one country had no independent right of access in the other. This result was challenged and, later in the same year, the Norwegian Supreme Court upheld the right of Swedish Saami to graze summer pasture in Norway according to the principle of use since time immemorial (Strøm Bull, 2015). The court's decision notwithstanding, the Norwegian-Swedish Reindeer Grazing Convention of 1972 concluded 10 years' negotiation by reducing the area of pasture available to the northern Swedish group in Norway by a further 4,903 km^2 to just 3,150 km^2 (Koch and Miggelbrink, 2011). The herder's overall loss since 1919 was therefore 82%.

The 1972 Grazing Convention had a term of 30 years and, anticipating its expiry in 2002, a Norwegian-Swedish Reindeer Pasture Commission was convened in 1997 to '*investigate the question of whether one country's Saami reindeer herders will continue to require pasture in all or parts of the reindeer grazing areas covered by the Convention in the other country beyond the end of the current Convention*' (Government of Norway, 2001b). The Commission's report, submitted in 2001, was heavily criticized and, in the absence of an agreed basis for a new convention, the existing one was extended for 3 years to 2005 (Government of Norway, 2017). Sweden declined further extension after that and consequently there has been no convention on cross-border grazing between Sweden and Norway—beyond the principles set out in the Lapp Codicil—since then. The Swedes consider these principles sufficient but the Norwegians take the view that additional provisions in national law are necessary. Their argument is that the Codicil refers only to customary practice, not specific areas, and is therefore incompatible with modern regulations regarding the spatial definition and the temporal and numerical pattern of use of reindeer pasture. The reciprocal cross-border grazing areas currently under negotiation are clearly delineated in a document drafted by both sides (**Figure 3**). The current impasse regarding their use means that Norwegian herders have in effect lost their legal right of access to pasture in Sweden. In the view of the Norwegian government:

> *'Almost 12 years without a new convention is a very unfortunate situation. The Norwegian authorities have repeatedly pointed out to Sweden the importance of ratifying a new convention. Norway and Sweden have international legal obligations to Sami reindeer husbandry, including cross-border … herding. The Government aims to ratify a negotiated convention as soon as possible and will continue to exert pressure on Sweden [to this end]'* (Government of Norway, 2017, p. 60).

In the view of one herder:

> *"We cannot wait for the law. We, and our Swedish colleagues, agree that herding cannot stop. It must go on. So we have made our own private arrangements: we take our animals to Sweden and they bring theirs to Norway as before. Others are not so fortunate. It is*

now 15 years since there was a Convention on cross-border grazing. That is two generations of animals. So neither our reindeer nor our young people now have any experience or even memory of their traditional pastures across the border. How will they know how to use them if they are ever allowed to return? And how can you defend pasture from encroachment if you are never there?" (Ragnhild Sparrok Larsen, personal communication, 13 February 2020).

Withdrawal of Domestic Grazing Rights. The legal battle for the right to graze *utmark* which Saami reindeer herders in Norway fought across the 20th Century (above) was not won without casualties, the ghosts of some of which still walk abroad.

Concurrent with Professor Nielsen's study of rural settlement in south-eastern Norway at the close of the 19th Century (above), the government received persistent complaints from farmers about damage allegedly done by reindeer to fields, open meadows and hayracks (Supreme Court of Norway, 1981; Valstad, 1989). This resulted in the passing, in 1897, of an Act '*containing supplementary provisions concerning the Lapps and reindeer husbandry in those parts of the country south of the county of Finnmark*' (Government of Norway, 2001a, p. 79; Fjellheim, 2012, p. 129). The new law was swiftly implemented. A series of governmental executive orders (*kongelige resolusjoner* literally 'Royal resolutions') in 1899–1902 restricted reindeer husbandry to specified areas within the region. Herders outside those areas had no option but to move or to abandon pastoralism. They were in effect outlawed. Martin Jonassen, a spokesman for the southern Saami, was twice granted audience with Haakon VII, King of newly independent Norway. In 1906 and again in 1908 he presented and explained to the King the distress these measures caused (Oppdal, 2007) although apparently to no avail (Jonassen, 2017).

Some herders ignored the law and returned with their animals to areas from which reindeer had been banned: courts imposed fines for illegal grazing in 1907, 1909, 1942, 1944, 1947, and 1975 (Supreme Court of Norway, 1981). Such was the herders' persistence and, presumably also, so remote were the areas involved, that the effect of the ban was actually quite limited for some:

> '*... the ban imposed by the executive orders did not have any significant practical effects on reindeer husbandry in [the] Trollheimen [area] ... [Although it] continued for several decades ... [and] there is no evidence that it led to serious conflict with local people*'
>
> (Supreme Court of Norway, 1981).

Herders challenged the withdrawal of their right to graze both outside the designated reindeer husbandry areas and within such areas without landowners' permission in cases brought before the District Court (1976), the Court of Appeal (1978), and finally the Supreme Court which ultimately found against them (Supreme Court of Norway, 1981). The herders' persistence nevertheless bore fruit when, 3 years later, some of the land closed by executive order at the beginning of the century was once more opened to reindeer husbandry (Government of Norway, 1984).

Regulating Access to Pasture

> '*... society has a duty to help [reindeer herders] such that they can themselves better apportion and utilize their resources.*'
>
> (Ravna, 2011)

The fundamental right to graze *utmark* that emerged from the legal gyrations of the last century does not afford herders free access to pasture or complete freedom to organize grazing themselves (Government of Norway, 2016, p. 20). Herders' traditional regulatory mechanisms and systems of land tenure are explicitly subordinate to State management (Turi and Keskitalo, 2014). Each *siida* is obliged to maintain no more than a designated number of animals within designated seasonal 'pasture districts,' access to which follows a designated temporal schedule (Government of Norway, 2007, §§59–61. *Siida*: see **Box 2**). The current level and pattern of organization evolved from a system defined in the Reindeer Husbandry Act of 1933 which for the first time determined where and when reindeer might be pastured. Government bailiffs (*lappefogd*), appointed to enforce the regulations, had authority both to grant and to withdraw permission for herders to graze particular areas (Bjørklund, 2016). Their authority was enhanced in 1949 by the creation of a special force of 'reindeer police' (*reinpoliti*) but the bailiffs and the police were nevertheless deemed inadequate. Land use conflicts increased, both internally between *siida* and externally due, in particular, to encroachment—notably in the case of the damming of the Alta River (Brantenberg, 1985)—and this, together with policy makers' desire to 'modernize, rationalize and optimise' reindeer husbandry, led to a major revision of the entire regulatory system (Johnsen and Benjaminsen, 2017). A second Reindeer Husbandry Act (1978) broadened the scope and authority of the national Reindeer Husbandry Administration in a manner consistent with the view that '*central management [should be] free to organize reindeer husbandry in the manner that coincides with the prevailing policies ... it is up to the authorities to decide, within the framework of the law and its intentions, the division of districts, the allotment of production units, number of reindeer and so on, based on what is considered appropriate and justifiable*' (Government of Norway, 2001a, p. 124). This Act increased the breadth and complexity of government administration of reindeer pastoralism, further eroding Saami land tenure systems and management institutions and exacerbating tension between State administration and pastoralists which remains evident today (Ravna, 2011; Turi and Keskitalo, 2014; Benjaminsen et al., 2016a).

The judicialization of reindeer husbandry and, in particular, the setting of fixed boundaries resulted in '*stiffer [administrative] structures and less room for the solutions that the situation at all times requires*' (Government of Norway, 2017, p. 20). A third Reindeer Husbandry Act (2007), more sympathetic to the traditions, aspirations and methods of pastoralists—and, in this respect, considerably more in harmony with contemporary empowering of indigenous peoples of the North (Coates and Broderstad, 2020)—therefore relaxed the role of central administration and awarded herders greater self-determination (Government of Norway, 2017, p. 39). The principle of use since time immemorial was elevated to a '*central place in reindeer husbandry law … [and] … carries considerable weight in the setting of [seasonal pasture] boundaries …*' (Norwegian Reindeer Husbandry Administration, 2006, p. 2). The Act nevertheless retained the view that herders enjoy '*no common right to graze their animals wherever they choose*' (Government of Norway, 2016, p. 20) and its provision for the transfer to herders of responsibility for the division and use of pasture is effectively unworkable. Under the terms of the Act, grazing within 'pasture districts' is regulated by district boards, composed of local herders, which are required to develop rules of usage '*based on the traditional practice … [that] promote rational land use … [and that do not] conflict with* siida *rights established separately in law*' (Government of Norway, 2007, §59). The Act, however, neither clarifies these objectives nor provides any structure for the resolution of conflicts which arise where different objectives prove incompatible. The resulting frustration among herders (Turi and Keskitalo, 2014) is compounded by the fact that central authorities retain the right to reverse board decisions thereby effectively disempowering them (Government of Norway, 2017, p. 68). A herder who was involved in the drafting of the new Act summarized her experience thus:

> *"At first I was optimistic about this but my optimism drained away as the work progressed. They go around us and avoid the things that affect us. They do not understand our way of doing things. Sometimes it seems they do not even want to understand them. And there are no regulations on how the law should be applied: not one. This leaves people free to interpret the law however they wish. The result is chaos: it's a real mess."* (Inger Anita Smuk, personal communication, 12 February 2020).

The management of pasture and, specifically, of access to pasture is further complicated by the fact that grazing cannot be regulated independently of the aspirations and requirements of other land users. From a herders' perspective land use planning might legitimately be considered the way in which the State legitimizes loss of pasture through encroachment. This is the topic of the next section.

Land Use Planning and Encroachment

> *'The extensive nature of land use characteristic of reindeer husbandry can lead to substantial conflict [of interest where] land [is required] for building and other commercial activities.'*
> (Government of Norway, 2017, p. 52)

Weak protection of pasture

Loss of pasture is the greatest single threat to reindeer pastoralism in Norway today and herders and the Saami Parliament alike consider the strengthening of legal protection of grazing land a priority (Government of Norway, 2017, p. 69–70). The situation is paradoxical because grazing reindeer on *utmark* is already explicitly protected by law. The 2007 Reindeer Herding Act states specifically that '*The owner or [other] legitimate user must not use land … [to the] material disadvantage or inconvenience [of] reindeer husbandry*' and it grants herders the right of compensation for loss of pasture (Government of Norway, 2007, §4, §63). The protection afforded by the Act, however, is weak. Reindeer pastoralism does not have an exclusive right of access to pasture within designated reindeer grazing areas: herders are obliged to concede land to the development of infrastructure and activities including agriculture (Government of Norway, 2007, §19), local airports, hydro-electricity facilities (Nellemann et al., 2003; Bjørklund, 2016), linear structures (power lines, railways, roads [metalled and unmetalled]: Vistnes and Nellemann, 2001; Office of the Auditor General, 2004; Tyler et al., 2016), military training areas (Nellemann and Vistnes, 2002; Finn, 2019), mining operations (Johnsen, 2016; Eftestøl et al., 2019), wind farms (Skarin et al., 2015; Skarin and Alam, 2017; Strand et al., 2017), recreational facilities including private mountain huts (Lie et al., 2006; Anttonen et al., 2011), ski fields and walking, dog-driving, ski and snowmobile trails (Office of the Auditor General, 2004; Riseth and Johansen, 2018). All encroachment in reindeer husbandry areas requires a concession but planning authorities are liberal in their discretion: there is a gulf between the intention of the law and planning practice (Hanssen et al., 2018). Norwegian land management law requires consultation, participation, coordination and investigation, each stage scheduled in elaborate rules of process (Government of Norway, 2008). Regulations appended to the Planning and Building Act specify, in particular, that assessment of the potential impact of proposed measures on reindeer husbandry must evaluate the overall (i.e., cumulative) effects of encroachment and not just its specific effect(s) (Government of Norway, 2014: Appendix IV). Planning authorities are nevertheless empowered to rank different societal considerations and to disregard the interests of reindeer husbandry where other interests are afforded greater weight (Johnsen, 2016; Winge, 2016). The problem for herders is exacerbated by legal ambiguity (Ravna, 2011), extensive and burdensome bureaucracy and asymmetric negotiating procedures (Bjørklund, 2016; Winge, 2016), all compounded by a lack of consideration—or even understanding—of Saami tradition, aims and perspectives: '*… it seems difficult to get … elected officials to recognize that Saami interests are [categorically] different [from those of] other commercial or even recreational [activities]*' (Hanssen et al., 2018, p. 491; see also Wilson, 2003; Turi and Keskitalo, 2014; Bjørklund, 2016; Lawrence and Larsen, 2017; Persson et al., 2017; Finn, 2019). All these aspects are explicitly recognized, which is progress of a kind: '*The government sees a need to increase regional and municipal planners' knowledge of about reindeer husbandry, [and herders'] and reindeer husbandry authorities' knowledge about the Plan and Building Act*' and to facilitate, '*through increased understanding of reindeer husbandry's use of the land … smoother and more predictable land use planning*' (Government of Norway, 2017, p. 54).

The physical loss of pasture associated with construction is usually small and localized in extent (above). The extent of non-physical losses, by contrast, can be vast. Losses due to the withdrawal of grazing rights are extensive and conspicuous: the area of pasture lost following the closure of the border with Finland (above) is an obvious example. Losses resulting from avoidance behavior, by contrast, are extensive but inconspicuous.

Avoidance: the Expression of Reduced Value of Pasture

Avoidance is a behavioral response induced by the sight, sound, or smell of humans or human artifacts either directly perceived or associated through learning with infrastructure (Dyer et al., 2001; Barber et al., 2011; Brown et al., 2012; Shannon et al., 2014). The response is manifest as reduced abundance of the species of interest in the vicinity of stimuli—the so-called 'zone of avoidance.' Hesitant or re-routed passage of animals past, across or through infrastructure is symptomatic. Such responses indicate that the value of the site or area has been reduced insofar as animals are reluctant to use it. Avoidance has been reported in 234 species worldwide, among them reptiles, amphibians, birds and mammals, in nearly every type of habitat, at nearly every type of infrastructure and with or without human presence or traffic (Andrews, 1990; Forman and Alexander, 1998; Lawton et al., 1998; Trombulak and Frissell, 2000; UNEP, 2001; Nellemann et al., 2003; Fahrig and Rytwinski, 2009; Benítez-López et al., 2010; Chen and Koprowski, 2019).

Avoidance in *Rangifer* ranges from modest withdrawal to complete abandonment of part of the animals' normal range. Zones of avoidance, within which the density of animals is typically 50–95% lower than in control areas, typically extend 2.5–5 km from infrastructure (e.g., Wolfe et al., 2000; Vistnes and Nellemann, 2008; Skarin and Åhman, 2014; Engelien and Aslaksen, 2019). Avoidance is not usually evident within the zone: of 85 studies, only 13% detected avoidance within 2 km of infrastructure while 83% detected avoidance when comparing the density of animals <2 and >2 km from infrastructure (Vistnes and Nellemann, 2008; see also Skarin and Åhman, 2014; Plante et al., 2018). Abandonment of pasture around infrastructure, resulting in fragmentation of the range, has been observed in both wild and domesticated *Rangifer*. A spectacular example is the way in which the formerly contiguous range of wild reindeer in Norway has been fragmented by infrastructure to such an extent that the animals are now managed as 23 independent populations (Andersen and Hustad, 2004; Panzacchi et al., 2013a). Avoidance and barrier effects (i.e., hindrance to passage) in *Rangifer* have been documented at roads (Cameron et al., 1992; Nellemann and Cameron, 1996, 1998; Vistnes et al., 2008; Beyer et al., 2016; Plante et al., 2018; Serrouya et al., 2020), power lines (Tyler et al., 2016), pipelines, seismic trails, oil well and mining sites (Nellemann and Cameron, 1996; Polfus et al., 2011; Johnson and Russell, 2014; Johnson et al., 2015; MacNearney et al., 2016), dams and hydroelectric development (Mahoney and Schaefer, 2002; Nellemann et al., 2003), wind turbines (Skarin et al., 2015, 2018; Skarin and Alam, 2017), hut resorts, ski trails, paths (Helle and Särkelä, 1993; Nellemann et al., 2000, 2001; Vistnes and Nellemann, 2001; Anttonen et al., 2011; Helle et al., 2012; Lemerises et al., 2018; Gundersen et al., 2019) and at forestry sites (Schaefer, 2003; Anttonen et al., 2011; MacNearney et al., 2016; Fryxell et al., 2020; for reviews see Wolfe et al., 2000; Vistnes and Nellemann, 2008; Skarin and Åhman, 2014). *Rangifer* are not unique in this respect. Similar responses have been observed in other large ungulates including Arabian gazelle (*Gazella arabica*, Ross et al., 2019), Balkan chamois (*Rupicapra rupicapra balcanica*, Kati et al., 2020), Eld's deer (*Cervus eldi*, Yan et al., 2013), elephant (*Loxodonta africana*, Orrick, 2018), elk (*Cervus canadensis*, Paton et al., 2017; Prokopenko et al., 2017; Spitz et al., 2019), guanaco (*Lama guanicoe*, Cappa et al., 2019), mule deer (*Odocoileus hemionus*, Northrup et al., 2015), pronghorn (*Antilocapra americana*, Jones et al., 2019), red deer (*Cervus elaphus*, D'Amico et al., 2016), wild boar (*Sus scrofa*, D'Amico et al., 2016) and wildebeest (*Connochaetes taurinus*, Stabach et al., 2016).

Avoidance is a graded response. The strength of expression of the behavior varies with the type of infrastructure and with the ecological setting of each encounter. Thus, levels of avoidance vary with age, sex and life-phase (e.g., migration, post-calving, over-wintering), and hence with the animals' imperative to stay or to move, and also with the proximity of other stimuli including other types of infrastructure, human activity and predators (Wolfe et al., 2000; Vistnes et al., 2001; Vistnes and Nellemann, 2008; Fortin et al., 2013; Panzacchi et al., 2013a; Skarin and Åhman, 2014; Wilson et al., 2016; Plante et al., 2018; Skarin et al., 2018). Forestry practices, including the creation of logging roads, cuttings and transitional forests, encourage predators (e.g., wolves *Canis lupus*) which in turn provoke avoidance (Leech et al., 2017; Mumma et al., 2018) and even the abandonment of parts of the animals' former range (Schaefer, 2003; Anttonen et al., 2011; Fortin et al., 2015; Rudolph et al., 2017). Extensive developments and high levels of disturbance (e.g., vehicular and foot traffic) induce stronger avoidance than smaller developments and low levels of traffic (Nellemann et al., 2010; Lemerises et al., 2018; Fryxell et al., 2020). Thus, avoidance typically occurs at rate of a 0–50% reduction in use of land up to 1 km from trails, small power lines and wooden telephone poles, at around 50% 2.5–5 km from large, single power lines and roads, and at 50–95% 5–10 km from large industrial developments (e.g., dams and hydroelectricity stations, multiple power lines and pipelines, mines and oil field complexes) and hut resorts (Wolfe et al., 2000; Vistnes and Nellemann, 2008; Skarin and Åhman, 2014; Engelien and Aslaksen, 2019). Animals also practice trade-offs: adult *Rangifer* males in particular seem sometimes actively to seek out structures that afford dry ground, shade or exposure to breezes (e.g., buildings, underpasses, elevated concrete pads) which apparently provide relief from biting insects (Wolfe et al., 2000; Vistnes and Nellemann, 2008; Skarin and Åhman, 2014). Finally, avoidance and barrier effects may be short-lived or may persist for years or even decades after the construction of infrastructure. In Norway, for instance, the Setesdal-Ryfylke population of wild reindeer continued to avoid those parts of their range associated with dams, roads and high-voltage power lines for more than 30 years after these were built (Nellemann et al., 2003) and barrier effects and avoidance of power lines, in particular, have been observed to persist for years (Nellemann et al., 2003; Reimers et al., 2007) or even decades after construction (Vistnes and Nellemann, 2001; Vistnes et al., 2004). Caribou in Alaska, likewise, avoided the infrastructure and abandoned the area around the Prudhoe Bay-Kuparuk oil fields for up to 50 years after development started there (Nellemann and Cameron, 1998; Joly et al., 2006; Johnson et al., 2019). Responses of similar duration have been recorded in association with hydroelectric

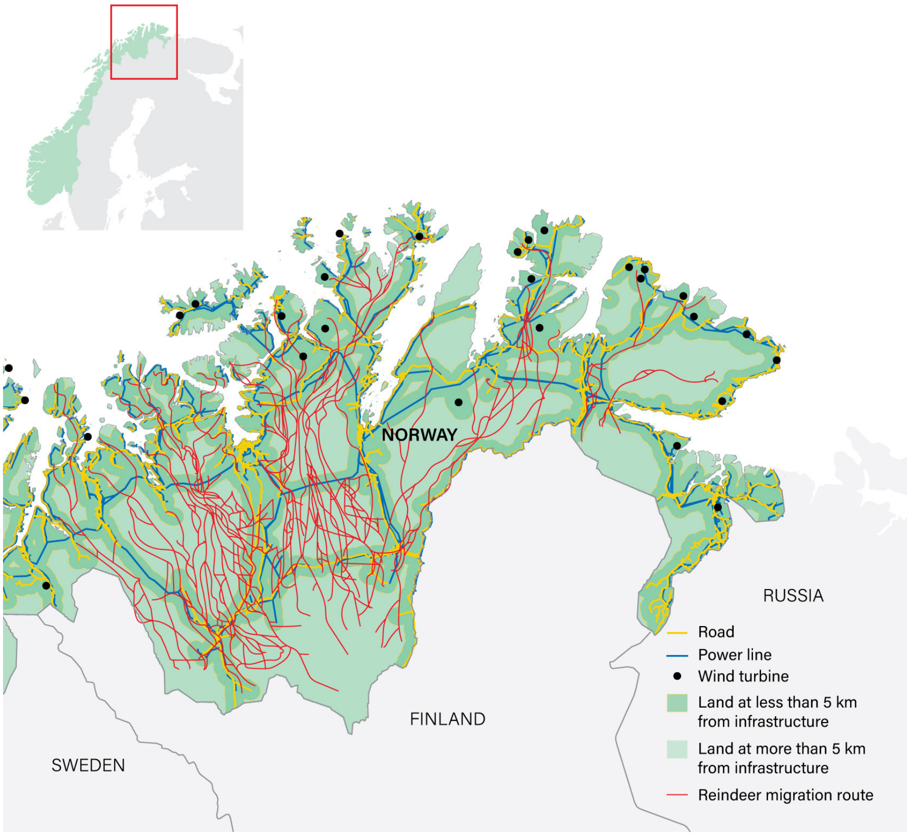

FIGURE 22 | Encroachment: map of reindeer migration routes and infrastructure in East and West Finnmark reindeer pasture areas (**Figure 3**). There are 150 sites in this area where reindeer traversing their traditional migration routes between summer pastures at the coast and winter pastures inland (red lines) are obliged to cross roads or pass beneath high voltage power lines. Sources: Infrastructure from the Norwegian Mapping Authority; migration routes from Vorren (1962).

developments and with logging (Mahoney and Schaefer, 2002; Schaefer, 2003).

The area of undisturbed pasture within the Saami reindeer husbandry area (i.e., land more than 5 km of infrastructure) decreased by 71%, from ~134,000 km^2 in 1,900 to 40,000 km^2 in 2019 (**Figure 18**). Approximately 102,000 km^2 (72%) of the total area (141,000 km^2) now lies within the 5 km impact zones where animals' use of pasture is likely to be reduced through avoidance. A corollary is that grazing pressure within in the remaining 28% low impact areas is likely to have increased correspondingly. The situation is exacerbated by the distribution of infrastructure. Roads, power lines and recreational huts are scattered across the Saami reindeer husbandry area. Even in northern Norway, the most remote part of the country, reindeer migration routes cross infrastructure at 150 sites (**Figure 22**). *Rangifer* commonly seem reluctant to approach and, where appropriate, to cross infrastructure (i.e., roads), and intersections of this kind therefore represent obstacles that impede and delay their passage (Wolfe et al., 2000; Dyer et al., 2002; Cameron et al., 2005; Degteva and Nellemann, 2013; Panzacchi et al., 2013a,b; Muhly et al., 2015; Skarin et al., 2015; Wilson et al., 2016).

Avoidance behavior is as prevalent and pronounced as its effect on the distribution of animals is inconspicuous and technically demanding to detect. Two alternative approaches are commonly used to quantify it. The first involves infrequent observation of the distribution of a large number of animals (usually a significant proportion of a herd or population) in relation to infrastructure. This approach is necessarily spatially extensive. To confirm or refute the presence of a zone of avoidance along, say, 50 km of road requires recording the position of animals within an area of 1,000 km^2, i.e., 50 km (the length of the road) × 10 km (twice the width of the suspected zone) × 2 (each side of the road). Counts are usually made from fixed wing aircraft, helicopters, or snowmobiles [or on foot along transects where the metric is animal sign (e.g., pellet groups) rather than animals themselves]. The obvious logistic constraint involved in such work means that data are normally limited to just one sample per season, effectively yielding sporadic 'snapshots' of the distribution of animals. This is a severe limitation in the case of a long-distance migratory species like *Rangifer*. The second approach involves frequent observation of the distribution of animals in relation to infrastructure made using GPS localization transmitters mounted on collars which the animals wear around their necks. This method generates vast amounts of precise data about the pattern of movement of the marked animals. Sample sizes,

TABLE 2 | Comparison of characteristics of studies which have drawn opposite conclusions about the effect of infrastructure on *Rangifer*.

Impact of infrastructure	Funding		Journal impact factor (JIF)	Proportion of papers published in journals with JIF >2	Number of radio-collared animals in GPS studies (by source of funding)	
	Industry	Government or research council			Principally industry	Principally government or research council
	% (*n*)	% (*n*)	Mean (SEM, *n*)	% (*n*)	Mean (min. – max., *n*)	Mean (min. – max., *n*)
Negative	19% (8)	81% (35)	2.91 (0.19, 43)	74% (43)	0	97 (23–510, 34)
Positive, minor or none	55% (6)	45% (5)	1.76 (0.31, 11)	9% (11)	23 (14–32, 4)	24 (14–39, 2)
	a	b	c			

Conclusions are classified as either (i) negative impact (avoidance or cumulative impact), or (ii) positive, minor or no impact. The Table compares conclusions in relation to source of funding and the impact factor of the scientific journals in which the studies were published (source: Thomson-Reuters ISI database using the search term <Rangifer and Avoidance*> 2007–2020; accessed 12 May 2020) and to the number of radio-collars deployed in studies which used GPS tracking to record the dispersion of animals in relation to infrastructure (source: Thomson-Reuters ISI database using the search term <Rangifer* and GPS> 2011–2020; accessed 11 July 2020).*
SEM, Standard error of the mean.
a χ^2 [1, n = 54] = 4.17, p < 0.05.
b z = 3.157, df = 53, p < 0.01.
c χ^2 [1, n = 54] = 15.72, p < 0.001.

however, are usually small: studies typically monitor just some tens of individuals that, in turn, usually constitute a tiny fraction of the population of interest. Both approaches thus have limitations but methodology is not the only factor that influences the likelihood of detecting avoidance: source of funding is also a determinant.

In Norway, like many other countries, developers are required by law to assess the environmental impact of their activity. Assessment is not invariably independent and impartial. Many examples of such work being carried or contracted out by the developers themselves confirm the wisdom of the proverb that 'He who pays the piper calls the tune' (Oreskes and Conway, 2010). We examined potential sponsor bias in the conclusions of 54 studies of the effect of human activity and/or infrastructure on spatial distribution and range use in *Rangifer*. The studies, all published since 2007, were recovered from the Thomson Reuter ISI database using the search criterion <Rangifer* avoidance*>. We classified the principal finding of each study as either (i) negative impact or (ii) low impact (positive, minor negative, or no avoidance). We also classified each study as either (i) funded wholly or in part by a developer (usually an industrial concern responsible for the installation and subsequent use of infrastructure) or (ii) funded by government agencies or research councils. Remarkably, a significantly lower proportion of studies funded by industry detected negative impact of encroachment. Of the 54 studies, 43 (80%) concluded that *Rangifer* were affected negatively by infrastructure or human activity but of these just 8 (19%) were funded by industry while 35 (81%) were funded by non-industry sources ($p < 0.05$; **Table 2**). The apparent influence of source of funding on the likelihood of detecting avoidance is also evident in the subset of studies that used GPS tracking to record the position and movements of *Rangifer* in relation to infrastructure. Of 34 (85%) of 40 such studies that detected negative impact of infrastructure, all were funded principally by non-industry sources: none of those funded by principally by industry detected negative impact (**Table 2**).

It may be significant that GPS-based studies which detected significant negative impact of infrastructure on *Rangifer* have consistently used substantially larger sample sizes than those, including those funded by industry, which detected positive, minor or no impact (mean number of collared animals per study: negative impact 97, low impact ≤24; **Table 2**). GPS tracking potentially provides important insight about animal movements but may also mislead where researchers, constrained by cost, deploy too few units thereby unwittingly diminishing their ability to draw robust population-level inferences from their results (Leban et al., 2001; Lindberg and Walker, 2007; Hebblewhite and Haydon, 2010). Consistent with this, studies which have reported low impact have generally published in journals with a lower impact factor (JIF) than those which have reported negative impact [mean JIF: low impact 1.76 (0.31 SEM), high negative impact 2.91 (0.19 SEM), $p < 0.01$; **Table 2**]. Indeed, only one (9%) of 11 studies which have reported low impact was published in a journal with JIF >2 compared to 74% of those which have reported negative impact ($p < 0.001$; **Table 2**). There are several potential explanations why particular classes of results come to be associated with more or less highly rated scientific journals, respectively, but it is not our intention to examine these here. It is sufficient to note that avoidance is considerably less conspicuous in studies funded by parties which have a vested interest in being disassociated from such behavior. Such bias undoubtedly contributes to the tendency for non-physical losses of reindeer pasture to fade from public awareness. We return to this in the Discussion.

DISCUSSION

In this paper we returned to the suggestion that the effects of human intervention and, in particular, the loss of pasture through various forms of encroachment, dwarf the putative effects of climate change on Saami reindeer husbandry in Norway (Tyler et al., 2007). Our approach has been to juxtapose examination of the characteristics and influence of climate and encroachment on the resource base of this pastoral grazing system. We made five principal observations. First, northern reindeer pasture lands are warming and seem likely to continue to do so. Second, semi-centurial (50 year) trends notwithstanding, seasonal weather conditions show a high degree of annual and decadal variation: local ambient temperature, precipitation and the characteristics of the snowpack remain highly unpredictable on both time-scales. Third, warming has both positive and negative effects on ecosystem services for reindeer in Fennoscandia: the role of climate change as a driver of change in reindeer pastoralism is neither temporally nor spatially uniform, nor even clear. In contrast, fourth, the effects of human intervention on reindeer pastures throughout Norway are consistently negative. Saami reindeer pastoralists in Norway struggle with loss of pasture from physical encroachment and from administrative encroachment which erodes their independence and constrains their freedom of action on the land that remains available to them. Both are conspicuous, pervasive and continuing effects and they represent the principal threat to reindeer pastoralism in Norway today. Herders resist and, in doing so, provoke negative public discourse about their way of life: Saami reindeer pastoralism is consequently perceived as—and indeed is—problematic. It is so, fifth, because it is extensive pastoralism and, as such, it is confronted by myriad administrative, economic, legal and social constraints of a kind which bedevil extensive pastoral grazing systems across the globe.

Weather Over Reindeer Pasture: Trends, Variation and Effects

Local data demonstrate clearly that Finnmarksvidda has become progressively warmer and wetter across the last 50 years (**Figures 8**, **9**, **11–15**). The pattern of development of the weather is not unique to this area: similar trends (i.e., generally warmer winters, increased precipitation in winter, shorter period of snow cover, earlier melt, later freeze up and hence longer plant growing season) are evident across northern Fennoscandia (Førland et al., 2004; Markkula et al., 2019). A major point of interest is whether these trends will persist. Several projections are available (Räisänen, 2012; Hanssen-Bauer et al., 2015, 2017; Benestad et al., 2016) and we chose a 'middle of the road' emission scenario with which to project changes in temperature and precipitation across the present century (**Figure 8**). Projections, however, are not forecasts (**Box 3**): uncertainty arises because future greenhouse gas emissions are unknown, because of flaws and deficiencies in the models, and because of internal variability on both annual and decadal scales (Hawkins and Sutton, 2009, 2011; Hanssen-Bauer et al., 2017). We therefore validated projections for Finnmarksvidda externally by comparing them with empirical field data. We found that the projection reproduced the development of mean annual temperature measured locally across the period 1985–2018 remarkably well (**Figure 8C**). The climate models we applied evidently performed well and the downscaling procedure nicely captured the way in which large-scale climate has influenced ambient temperature over Finnmarksvidda. On this basis, therefore, it is not unreasonable to interpret the trajectory of the *projection* forwards from 2018 as a *prediction* (**Box 3**) and hence to conclude that Finnmarksvidda is moving into a phase in which the weather will on average be warmer than at any time during the last 100 years.

The fit between projected and observed precipitation, on the other hand, was less convincing (**Figure 8D**). The model clearly underestimated the observed trend. Precipitation over Finnmarksvidda followed the 90 percentile of the model ensemble. This is curious because in other areas models overestimate observations (e.g., Svalbard; Hanssen-Bauer et al., 2019). The difference is conceivably due to internal climate variability which is a major source of uncertainty in regional precipitation models (Hawkins and Sutton, 2011). Such variability may have amplified the climate change signal of recent global warming or alternatively models may currently underestimate the local effect of the climate change on precipitation. Either way, the trajectory for precipitation from 2018 remains highly uncertain.

Having elevated the projection of temperature to a prediction, it is apposite to consider the potential consequences of warming for reindeer and hence for Saami reindeer pastoralism. The concept of 'warming' has beguiling simplicity in this context. The effects of warming on habitat services provided by tundra, taiga and boreal forest are diverse and complex. The boreal zone is cold and, not surprisingly, plants throughout it generally respond positively to warming during the growing season (Walker et al., 2006; Prevéy et al., 2019). Indeed, recent warming is considered a principal cause of the current greening of the Arctic (Pattison et al., 2015; Zhu et al., 2016). The effects of warming on ecosystem function and species' performance, however, are both temporally and spatially heterogeneous and, in particular, scale dependent. The positive effects of warming on plants, plant communities and biotypes are moderated and even reversed locally by a range of non-climate factors including geomorphology, surface hydrology and other features of the physical environment (Lara et al., 2018; Myers-Smith et al., 2020), species type and community type and composition (Elmendorf et al., 2012; Gruner et al., 2017), and grazing by vertebrates (Post and Pedersen, 2008; Bernes et al., 2015; Bråthen et al., 2017; Vanneste, 2017; Løkken et al., 2019; Andruko et al., 2020), invertebrates (Bjerke et al., 2017) or both (Gamm et al., 2018). The same applies in the reindeer pastures of northern Fennoscandia. The effects of warming on the performance of plants and plant communities there, too, are modulated by interactions between species and species groups (plants, lichens and herbivores), soil nutrient availability, inter-annual variation in weather conditions and human activity and consequently neither the magnitude nor even the sign of responses to warming are reliably predicted by changes in temperature alone (Olofsson et al., 2009; Grau et al., 2012; Bernes et al., 2015; Bjerke et al., 2017; Kaarlejärvi et al., 2017; Maliniemi et al., 2018; Markkula et al., 2019; Tømmervik et al., 2019).

The situation in the non-growing season (winter) is similar. Assessing the potential consequences of winter warming for reindeer is complicated by the contradictory nature of the signal and its effects. The weather on Finnmarksvidda has changed considerably over the last 50 years: there is and are, for instance, currently more precipitation (**Figure 14**), greater depth of snow (**Figure 15**) and more thaw days in winter (**Figure 12**) than 50 years ago. The regression estimates for 2018 for these parameters fall outside their former range and what is statistically 'normal weather' today would quite properly have been denoted statistically 'extreme weather' then. The trends are clear but their potential consequences, should they continue, are not. It is frequently suggested that warming in winter is inevitably likely to have a negative effect on reindeer pastoralism owing to reduced availability of forage in winter (through 'icing'; above) and to the constraining of herders' options for the use of pasture (e.g., Reinert et al., 2009; Bartsch et al., 2010; Risvoll and Hovelsrud, 2016; Turunen et al., 2016). Winter warming, however, also leads to increased ablation of snow (*sensu* Forchhammer and Boertmann, 1993), shorter winters (fewer days of snow cover; **Figure 16**), and to earlier and extended growing seasons (**Figure 11**), all of which are conditions associated with increased body growth in *Rangifer* (Pettorelli et al., 2005; Couturier et al., 2009; Tveraa et al., 2013; Albon et al., 2017) and, at least in some cases, population increase (Tyler et al., 2008; Post et al., 2009a). Positive effects of warming like these, together with a projected reduction in depth of snow on Finnmarksvidda toward the end of the 21st Century (Hanssen-Bauer et al., 2015, 2017), suggest that the overall trend is toward increasingly favorable winter grazing conditions for reindeer there, at least in the long term.

The situation is further complicated by the large inter-annual and decadal variability in the climate of the boreal zone and to the relatively small signal-to-noise ratio at many sites, net warming notwithstanding (ACIA, 2005; **Figures 2**, **8**). Winters on Finnmarksvidda, for instance, were consistently colder in the 1980s but consistently warmer in the early 1990s than indicated by the linear regression line (**Figure 9**). The duration of snow cover likewise was consistently longer than expected in the 1990s (**Figure 16**) and there was considerably less depth of snow than expected throughout the first decade of the present century (**Figure 15**). Projections from numerous climate models suggest that the inter-annual and decadal variability in conditions characteristic of the boreal zone will persist, albeit around a new level. The effect of this, we suggest, will be perpetuation of the current pattern whereby the effects of general warming on grazing conditions are alternately amplified and then diminished across the region.

Our analysis also revealed substantial local variation in weather conditions. We have already noted how in some areas of Norway the normal pattern of migration, in which herders and their reindeer move inland in winter to escape difficult snow conditions at the coast, is reversed where local conditions render coastal pastures snow free in winter (**Box 1**). Conditions also vary substantially within seasonal pasture areas. In the 1990s, for instance, the weather was markedly wetter than expected at Suolovuopmi and at Kautokeino but not at four adjacent sites (**Figure 14**). There were likewise on average nearly twice as many thaw days in winter at Karasjok (mean 37 days · winter^{-1}, 7.9 SD) than just 70 km away at Sihccajarvi (mean 21 days · winter^{-1}, 7.9 SD; data 1969–2018; **Figure 12**). The unstable winter temperatures at Karasjok, reflecting its relatively low altitude (140 m a.s.l.), conceivably impinge on the snowpack, rendering it denser and harder and, in turn, rendering winter grazing conditions more difficult for reindeer there compared to at Sihccajarvi (375 m a.s.l.). This could easily be tested. Local variation in weather conditions that influence the performance of wild *Rangifer* translate into spatial heterogeneity in individual and population responses to climate change (e.g., Post, 2005; Post et al., 2009a; Hansen et al., 2019b) and there is no reason why this should not be the case for domesticated *Rangifer*, too. This also could easily be tested.

Climate change is widely presented as a threat to the condition of reindeer pasture and, by extension, to reindeer pastoralism. Its potential to corrupt grazing conditions in summer or winter or in both is consistently emphasized in studies and reports, irrespective of whether this was their primary focus (e.g., Weladji and Holand, 2003; ACIA, 2005; Rees et al., 2008; CAFF, 2013) or merely their justification (e.g., Paoli et al., 2018). Emphasis solely on negative effects of climate change, however, is partial and perhaps premature. Trends in weather conditions, and the specific effects of variation in weather on ecosystem services, vary qualitatively and quantitatively, temporally and spatially around northern Fennoscandia (Markkula et al., 2019 and above). The influence of climate change on reindeer pasture there is neither uniformly positive nor uniformly negative: it is a combination of both. The chief feature of the role of human intervention on reindeer pasture, by contrast, is consistently negative.

Human Intervention on Reindeer Pasture: Out of Sight, Out of Mind

Climate is a forcing agent: it modulates the performance of reindeer through its influence on weather and pasture conditions. Humans are also forcing agents and their intervention has eroded and is continuing to erode the resource base of the reindeer extensive grazing system. In this paper, as previously (Tyler et al., 2007), we distinguished two aspects of such erosion: physical loss and non-physical loss of pasture. Physical loss of pasture as a result of construction, especially construction of infrastructure, and of the transformation of uncultivated land (*utmark*) into other biotopes, is tangible, conspicuous but clearly only limited in extent. Buildings, infrastructure and agriculture cover no more than 1% of the county of Troms and Finnmark which is the principal reindeer husbandry area in Norway (above). Non-physical losses of pasture due to the withdrawal of grazing rights and to the reduction in the value of pasture, by contrast, are neither tangible nor conspicuous. Their extent, however, is vast: 50% of traditional winter pasture was lost when the border with Finland was closed; 72% of remaining pasture lies within 5 km of infrastructure and is therefore likely to be under-used by reindeer to some degree. Though potent and prevalent, such losses are prominent neither in official nor public discourse concerning the state of reindeer pastoralism. Avoidance behavior, for instance, is afforded but one sentence in the recent White Paper on reindeer husbandry (Government of Norway, 2017; but see Frostating Court of Appeal, 2020a). There are several reasons for this.

First, short-term memory. Border closures quickly fade from public awareness. This is not surprising: remote land lying beyond remote borders is literally out of sight and events of more than half a century ago (in the case of the closure of the Russian and the Finnish borders) are not surprisingly out of mind. The closure of the border with Sweden is more recent and has not been forgotten, albeit that negotiations to reopen it have stagnated (above). The area of pasture potentially available to Norwegian Saami in Sweden (14,000 km^2), however, is equivalent to just 10% of the Saami reindeer husbandry area in Norway and the problem probably achieves little prominence for that reason.

Second, pragmatism. Government policy regarding the management of reindeer pastoralism in Norway is sharply focussed on the productive performance of the animals and on the environmental consequences of grazing. Management policy has been supported and encouraged by evidence of poor body growth of reindeer and of density-dependent changes in the biomass and botanical composition of reindeer pasture, especially in the north of the country (Fauchald et al., 2004; Bråthen et al., 2007; Ims et al., 2007; Tømmervik et al., 2009). These perceived evils have been attributed to overgrazing associated with their being 'too many reindeer' (e.g., Office of the Auditor General, 2004; Riseth and Vatn, 2009; Pape and Löffler, 2012; Benjaminsen et al., 2016b, Skonhoft et al., 2017). From this interpretation stems policy and legislation aimed specifically at reducing numbers of reindeer and thereby in some unspecified way achieving 'ecological, economic and cultural sustainability' of reindeer pastoralism (Government of Norway, 1992, 2007, 2017; see also Tyler et al., 2007). The terminology is unfortunate: 'overabundance' ('too many' animals) and 'overgrazing' are diffuse, plastic concepts in ecology. They are neither generally applicable nor, often, even meaningful outside the confines of definitions specific to the ecological settings of particular classes of cases (see Caughley, 1981; Behnke and Scoones, 1993; Behnke, 2000; Mysterud, 2006). Domesticated reindeer in Norway obviously impose heavy grazing pressure on *utmark*: 215,000 animals within 141,000 km^2 (**Box 2**) constitute an average density of 1.5 reindeer $\cdot$ km^{-2}. This is six times the average density of domesticated reindeer in Eurasia as a whole (0.25 reindeer $\cdot$ km^{-2}; **Box 1**). However, where—and for whatever reason—it is considered desirable to reduce stocking rate, invoking value-laden terms like overabundance and overgrazing achieves nothing. Far from serving to enrich understanding of the biological basis of the situation, it serves only to direct attention toward the activity of pastoralists who influence animal numbers and hence the grazing system from within, and away from those parties who influence it from without. State management, however, is pragmatic: herders are less empowered than landowners (including the State) who have personal, commercial or national interests at stake. It is therefore invariably simpler to manipulate stocking rate by legislating for reduction in numbers of animals than for an increase in the area of pasture on which they may graze (but see Supreme Court of Norway, 2017).

Third, myopia. Encroachment on *utmark* occurs piecemeal. The number of structures (of whatever kind) and the extent of commercial and recreational activities all increase incrementally, each encroachment contributing just a fraction of the total. Recreational huts, single-track access roads and other small features scattered in the terrain are likely to pass the casual observer unnoticed and to slip easily through planning authorities' bureaucratic nets. Yet huts, though small, are built in their thousands (**Figure 19**), access roads carry not only workers but walkers, and infrastructure is usually aggregated where the natural relief affords convenient passage for humans and animals alike (e.g., Nellemann and Cameron, 1996; Forman and Alexander, 1998; Benítez-López et al., 2010; Panzacchi et al., 2013a; Plante et al., 2017). Even large scale infrastructure, likewise, may be rendered effectively invisible. This occurs in several ways. Ambiguity is one. The validity of the claim that 'that reindeer husbandry's land area in Finnmark did not change significantly [i.e., was not reduced] in the period 2001–2011' (Government of Norway, 2017, p. 54) depends on how the word 'significantly' (*nevneverdig* in the original) is construed: the rate of building there proceeded unabated through this period (**Figure 19**). Scale is another. Large local encroachment seems quite small when viewed in sufficiently broad perspective. The Mauken-Blåtind military training area near Tromsø (**Figure 3**), for instance, extends over 200 km^2: this is just 1% of the Troms reindeer husbandry area (18,718 km^2) but fully 12% of Mauken reindeer husbandry district (1,699 km^2). Finally, courts evaluating herders' claims for damages confine their deliberations to the impact of the infrastructure for which the developers, as defendants, are responsible: other infrastructure falls outside their jurisdiction (e.g., Hålogaland Court of Appeal, 2019; Frostating Court of Appeal, 2020b). Animals, however, make no such distinction. They respond to the sum of constraints and their responses reflect the cumulative effect of encroachment (Theobald et al., 1997; Johnson et al., 2005; Krausman and Harris, 2010). By narrowing the focus such that the effect of each new intrusion is evaluated in isolation, impact is packaged and presented in doses small enough to be acceptable to the public and to planners alike and hence falls from the discourse. The concept of cumulative effects of encroachment on reindeer pasture is officially recognized; it is also officially recognized that it is not currently implemented in the planning process but remains an ideal which administrators ought to embrace (e.g., Government of Norway, 2017; Troms County Municipality, 2018).

Encroachment is not the only non-climate anthropogenic factor which influences the resource base for reindeer. Manipulation of the number of animals is another. The data and the interpretation of data on numbers, however, are contentious. From 1970 to 2010 the number of domesticated reindeer in Norway almost doubled (Tømmervik and Riseth, 2011); in the West Finnmark reindeer pasture area (**Figure 3**) it more than doubled, rising apparently from a long-term stable level of around 40,000 to around 100,000 animals (**Figure 23**). The increase has been ascribed to the combination of socio-economic factors that made reindeer herding an attractive option for young Saami and to government economic support designed to stimulate production specifically by increasing numbers (Government of Norway, 1992, p. 36). The increase had two

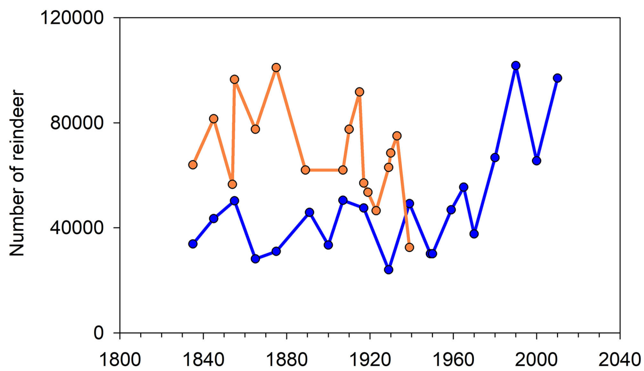

FIGURE 23 | Contrasting accounts of the development of numbers of reindeer in West Finnmark reindeer pasture area (**Figure 3**) across the last two centuries. The lower curve (blue) is based on official records (Tømmervik and Riseth, 2011) while the upper curve (orange) is based on herders' estimates (Sara et al., 2016). Sara et al. (2016) attribute the difference between the level of the two curves to herders' reluctance to declare the true size of their herds, leading to chronic underestimation of numbers in the official record (blue) before relatively rigorous counting procedures were introduced toward the end of the 20th Century. The accuracy of neither herders' estimates nor official records before then is known.

TABLE 3 | Land use conflicts of the kinds outlined in this paper are not unique to Saami reindeer husbandry in Norway: they are a feature of extensive pastoral grazing systems across the globe.

Source or cause of conflict	Saami reindeer pastoralism in Norway	World pastoralism (People) [Source]
Tenure reform	Closure of borders. Withdrawal of grazing rights [39]	Botswana (Ngami) [3] China [21] Kenya (Massai) [23] Mongolia [43] Southern Africa [7] Syria (Bedouin) [11]
Expansion of farming or forestry onto traditional pastoral rangeland	Locally significant [39]	Cameroon [33] India (Bhotiya, Gujar, Tolchha) [6, 31] Kenya (Orma and Wardei) [28] Nigeria (Fulani) [17] Mali [33]
Wildlife management (including protection of predators)	Widespread [24, 41]	Cameroon [40] Finland [15] India [30] Kenya [35] Nepal [36] Afghanistan, Pakistan and Tajikistan [10] Sweden [19] Tanzania (Maasai) [27]
Industrial development (minerals)	Nussir copper mine and Biedjovággi gold and copper mines [20]	China [18] semi-arid Africa [4] Sweden (Saami) [16] Tanzania [22]
Industrial development (energy)	Widespread (power lines, dams, wind turbines) [39]	Kenya [oil, 12] Ethiopia [hydroelectricity, 14] Sudan (Misseriyya) [oil, 37] Peru [hydroelectricity, 25] Russia (Nenets) [9]
Linear infrastructure	Widespread (roads, power lines) [39]	Kenya [26, 38] Russia (Nenets) [9] South Africa [8, 29]
Military training areas	Mauken-Blåtind military training area [13, 32]	Israel (Bedouin) [2]
Intervention (de-stocking) to reverse perceived overgrazing	Finnmark [39]	Azerbaijan [34] China [18] Kenya [5] Southern Africa [1] USA (Navajo) [42]

The Table matches eight types of land use conflict prevalent in Saami reindeer pastoralism with corresponding examples from pastoral systems elsewhere in the world.

Sources: (1) Abel (1993), (2) Abu-Rabia (1994), (3) Basupi et al. (2017), (4) Blench (1996), (5) Boles et al. (2019), (6) Dangwal (2009), (7) Davies et al. (2020), (8) Dean et al. (2018), (9) Degteva and Nellemann (2013), (10) Din et al. (2017), (11) Dukhan (2014), (12) Ennsa and Bersagliob (2016), (13) Finn (2019), (14) Fratkin (2014), (15) Heikkinen et al. (2011), (16) Herrmann et al. (2014), (17) Higazi (2016), (18) Ho (2016), (19) Hobbs et al. (2012), (20) Johnsen (2016), (21) Kreutzmann (2013), (22) Lange (2008), (23) Lesorogol (2008), (24) Linnell et al. (2001), (25) López-i-Gelats et al. (2015), (26) Løvschal et al. (2016), (27) Lyamuya et al. (2016), (28) Martin (2012), (29) McGahey (2011), (30) Mishra (2001), (31) Nautiyal et al. (2003), (32) Nellemann and Vistnes (2002), (33) Nellemann et al., 2019, (34) Neudert et al. (2013), (35) Okech (2010), (36) Oli et al. (1994), (37) Pantuliano (2010), (38) Said et al. (2016), (39) This paper, (40) Tumenta et al. (2013), (41) Tyler et al. (2007), (42) Wood (1985), and (43) Wu and Du (2008).

outcomes. The first was depletion of the resource base evident as an inverse relationship between the number of reindeer and the cover and biomass of dietary lichens (Office of the Auditor General, 2004; Tømmervik et al., 2004, 2009; Riseth and Vatn, 2009). This was an entirely predictable response. The second was a reversal of government policy and the introduction of legislation aimed specifically at reducing numbers (above). This has been criticized as misguided and theoretically unsound (Benjaminsen et al., 2015, 2016a, 2019; Marin et al., 2020). Sara et al. (2016), in particular, argued that the official census data were inaccurate and that, far from irrupting from a long-term stable low level, the increase in numbers actually only restored the population to its former level (**Figure 23**). Cast in this light, the point of interest is not the depletion of edible biomass that accompanied a doubling of the population but the reason for the remarkable abundance of forage, in particular lichens, immediately prior to this. Perhaps the richness of the sward and abundance of forage immediately prior to the increase was an artifact of several decades of under-grazing co-incidental with low numbers of reindeer in the 1950s and 1960s? The point will probably never be settled because there is no objective way of assessing the accuracy of the two contrasting sets of estimates (**Figure 23**). However, the very fact that numbers are contentious indicates broad acceptance of the fact that manipulation of population size is another non-climate determinant of the resource base.

The state and development of Saami reindeer husbandry are influenced by non-climate anthropogenic factors besides those that affect the resource base for reindeer. These include predation (Tveraa et al., 2014), where the intensity of predation is influenced through legislation designed to protect populations of predators (Tyler et al., 2007; Vuojala-Magga, 2012; Sjölander-Lindqvist et al., 2020), manipulation of the economic environment (Reinert, 2006, 2016; Tyler et al., 2007) and the evolution and development of the social and technological environments that influence all aspects of the pastoral way of life (Newhouse, 1952; Herbert, 1976; Government of Norway, 1992; Riseth and Vatn, 2009; Vuojala-Magga et al., 2011; Risvoll and Hovelsrud, 2016). All these in their separate ways influence the pastoral system and may therefore reasonably be assumed to reduce the proportional influence of climate variation on the dynamics of reindeer husbandry.

The influence of non-climate anthropogenic factors on reindeer pastoralism has recently received considerable attention (e.g., Brännlund and Axelsson, 2011; Vuojala-Magga, 2012; Löf, 2013; Turi and Keskitalo, 2014; Strøm Bull, 2015; Riseth et al., 2016; Tolvanen et al., 2019; du Plessis, 2020; Hausner et al., 2020; Kirchner, 2020, this study; see also López-i-Gelats et al., 2015, 2016). There is increasing recognition that the effects of human intervention may on occasion far exceed those of climate variation on reindeer pastoralism (Vitebsky, 2005; Anderson, 2006; Povoroznyuk, 2007; Tyler et al., 2007; Rees et al., 2008; Konstantinov, 2015; Uboni et al., 2016) particularly, but not exclusively, in the near-term (Kelman and Næss, 2019). We have focussed on non-climate loss of pasture which, in its various forms, is such a potent factor in Saami reindeer pastoralism in Norway. Norway is a wealthy country with highly developed and expanding infrastructure. Is the kind of human impact on pasture and on pastoralism evident there dependent on close proximity of grazing commons to industrialized society? Certainly not. No Supreme Court ruling (above), however favorable to pastoralism, can alter the fact that herders' requirements for land on which to graze their animals is fundamentally incompatible with the requirements of those who would use the same land for other purposes. Conflicts of interest, articulated in industrialized Norway in newsprint (and academic journals) and argued in meeting rooms, council chambers and courts of law, are a ubiquitous feature of this form of land use. Land use conflicts of the kinds outlined in this paper are not unique to Saami reindeer husbandry in Norway: they are a feature of extensive pastoral grazing systems across the globe (**Table 3**).

Saami reindeer husbandry is problematic (**Box 2**) precisely because it is extensive pastoralism and, like extensive pastoralism confronted by rapidly expanding modern society elsewhere around the globe, it struggles with inexorable piecemeal diminution of pasture and has to grapple with a plethora of administrative, economic, legal, social and societal obstacles associated with this. There is meager comfort in the realization that populations of wild ungulates are subject to some of same constraints (Lutz et al., 2003; Hobbs et al., 2008; Venier et al., 2014; Gordon, 2018). Nor is the prognosis encouraging: civil, commercial, industrial, military and private activity are set to expand throughout the Eurasian Arctic and sub-Arctic and to reduce the resource base of reindeer pastoralism still further (Latola et al., 2016; McCauley et al., 2016; Karlsdottir et al., 2017; Stephen, 2018; Kröger, 2019). On the other hand, the very existence of reindeer herding today, its shrinking resource base across the 20th Century (**Figure 18**) notwithstanding, is a testimony to the adaptability and resilience of herds and herders alike (see Heikkinen et al., 2007; Helle and Jaakkola, 2008; Brännlund and Axelsson, 2011; Vuojala-Magga et al., 2011; Jaakkola, 2014; Risvoll and Hovelsrud, 2016). Both features are likely to be sorely tested as development expands north.

Extensive pastoralism is a system that produces food and sustains culture on land too poor and in environments too harsh for any form of agriculture. Herders and their animals, the latter physiologically adapted to local conditions, have developed ways of life that enable them to thrive and successfully to exploit grazing opportunities afforded by scattered and ephemeral pasture resources. Mobility is the key: it is means by which herders and their animals adjust and adapt to changes in conditions and in levels resources irrespective of the cause(s) of those changes. This is evident wherever pastoralism is practiced, from parched savannah to frozen tundra or steppe. The mobility of herds and herders, however, is increasingly threatened by human population pressure, by piecemeal development and by the loss of grazing rights that are inconsistent with the urban and agricultural concept of rights achieved through ownership. For herders, constraints on movement are the primary threat while securing use of traditional grazing land is the primary goal.

AUTHOR CONTRIBUTIONS

NT and CN developed the concept of the review. All authors contributed to analyses and to writing the paper.

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Quantitative Spatial Ecology to Promote Human-Wildlife Coexistence: A Tool for Integrated Landscape Management

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Understanding, predicting and controlling animal movement is a fundamental problem of conservation and management ecology. The need to mitigate human-wildlife conflicts, such as crop raiding by large herbivores, is becoming increasingly urgent. Because of the substantial costs or the possibility of unsuitable outcomes on wildlife, managers are often encouraged to deploy interventions that can achieve their objective while minimizing the impact on animal populations. We propose an adaptive management framework that can identify cost-effective solutions to reduce human-wildlife conflicts, while also minimizing constraints on animal movement and distribution. We focus on conflicts involving animals for which conflict zones occupy only a portion of their home-range. The adaptive management approach includes four basic steps: define and spatialize conflict areas, predict animal distribution from functional connectivity and patch residency time, predict the impact of management actions on animal distribution, and test predictions and revise predictive models. Key to the process is development of a mathematical model that can predict how habitat-animal interactions shape animal movement dynamics within patch networks. In our model, networks consist of a set of high-quality patches connected by links (i.e., potential inter-patch movements). Inter-patch movement rules and determinants of patch residency time need to be determined empirically. These data then provide information to parameterize a reaction-advection-diffusion model that can predict animal distribution dynamics given habitat features and movement taxis toward (or against) conflict areas depending on management actions. Illustrative simulations demonstrate how quantitative predictions can be used to make spatial adjustments in management interventions (e.g., length of diversionary fences) with respect of conflict areas. Simulations also show that the impact of multiple interventions cannot be considered as simply having additive effect, and their relative impact on animal equilibrium distribution depends on how they are added and deployed across the network. Following the principles of adaptive, integrated landscape management, the predictive model should be revised as monitoring provides new information about the response of animals to the set of interventions. We contend that the proposed quantitative approach provides a robust framework to find cost-effective strategy toward sustainable human-wildlife conflicts.

Keywords: adaptive management, functional connectivity, human-wildlife conflict (HWC), movement ecology, patch network, quantitative ecology

INTRODUCTION

Increased rates of extinction of wildlife populations in association with human activity is the hallmark of the Anthropocene (Pereira et al., 2010; Richardson et al., 2020). Humans greatly impact wildlife by disrupting the distribution and behavior of animals globally (Gaynor et al., 2018; Tucker et al., 2018), and human footprint on the landscape is a key threat to wildlife across virtually all taxonomic groups (Turvey and Crees, 2019). The relation between wildlife and the available space is paramount for conservation (Rosenzweig and Ziv, 1999). Despite Aichi targets (CBD, 2018) aiming at increasing the amount of protected areas, a major the debate concerns how to allow biodiversity in human-dominated landscapes, such as land-sharing strategies (Green et al., 2005). Sharing space as a conservation model is contentious, however, as human-wildlife conflicts (HWC) are accelerating (Dickman, 2010). The International Union for the Conservation of Nature and the World Wildlife Fund consider HWC to be one of the main threats to biodiversity worldwide (IUCN, 2020; WWF, 2020).

These HWC, however, often stem from conflicts between humans about how to manage wildlife in shared landscapes (Peterson et al., 2010; Frank, 2016), and there is increasing recognition that the loss of species locally or strong spatial constraints on their movement can jeopardize management and conservation objectives, such as maintaining ecological integrity and ecosystem services (Ayantunde et al., 2011; Svenning et al., 2016; Wurtzebach and Schultz, 2016). There is growing interest in developing effective and efficient solutions toward sustainable HWC mitigation (Mumby and Plotnik, 2018), and integration HWC into landscape management will be key in this respect. This was well-coined two decades ago with the idea of reconciliation ecology, urging to rethink and design anthropogenic habitats so that their use is compatible with use by a broad array of other species (Rosenzweig, 2003).

While acknowledging that financial resources are often limited to carry out management actions (Richardson et al., 2020), the identification of cost-effective management interventions among a range of options can be difficult due to the multiple unknowns and uncertainties that characterize complex ecological systems (Ward et al., 2020). Understanding, predicting and controlling animal movement is key to designing anthropogenic landscapes that minimize the risk of negative interactions or maximize positive experience with wildlife. An additional challenge is to produce guidelines to assess the efficiency of management actions in the light of wildlife responses and human expectation. This is for instance the case with cross-boundary interactions that may occur at the interface between protected areas and their surroundings (Blanco et al., 2020) when animals move into (Piana and Marsden, 2014) and out of (Loveridge et al., 2017) protected areas to feed or migrate.

Here we propose an adaptive management framework (Walters and Hilborn, 1978; Richardson et al., 2020) that can be used to identify cost-effective solutions, while also minimizing constraints (e.g., avoid fencing off entire areas) on animal movement and distribution. We focus on conflicts involving animals for which conflict zones occupy only a portion of their home-range—a common situation for many species (e.g., Ripple et al., 2014; Soulsbury and White, 2015; Soliku and Schraml, 2018; Sigaud et al., 2020). The underlying idea is to use quantitative ecology to develop a species-specific predictive model of space-use dynamics, and then use this information to organize management actions over the landscape to divert animals away from conflict zones. The goal is not to completely constrain the movement of wildlife species but rather reduce human-wildlife interactions to socially acceptable levels. Our adaptive management approach includes four basic steps and a feedback loop (**Figure 1**): (A) define and spatialize HWC; (B) predict animal distribution from functional connectivity and patch residency time; (C) predict the impact of management actions on animal distribution; and (D) test predictions and revise the predictive model. Below we outline critical elements associated with each step of the management framework.

DEFINE AND SPATIALIZE HUMAN-WILDLIFE CONFLICT

Human–wildlife conflict generally stems from negative interactions between humans and wildlife. Conflicts can involve a range of outcomes of human-animal interactions, such as human deaths (e.g., predation, wildlife vehicle collision), disease spread, impacts on vegetation, dissemination of exotic plants into protected areas, livestock depredation, crop-raiding, and property damage (Ujvári et al., 1998; Packer et al., 2005; Ripple et al., 2014; Hadidian, 2015; Sigaud et al., 2020; Simon and Fortin, 2020). For example, from 2005–2016, 21 727 cases of crop raiding, 6,768 of livestock depredation, and 1,152 of property damage were reported in Kenya (Long et al., 2020). Human-wildlife interactions can thus occur at high frequencies, with even multiple conflict types happening concurrently over a given area (Jordán and Báldi, 2013; Sigaud et al., 2020). HWC should be assessed while considering that people's degree of tolerance for wildlife can be fundamental to finding solutions to promote human coexistence with dangerous or damage-causing species (Treves and Bruskotter, 2014; Struebig et al., 2018).

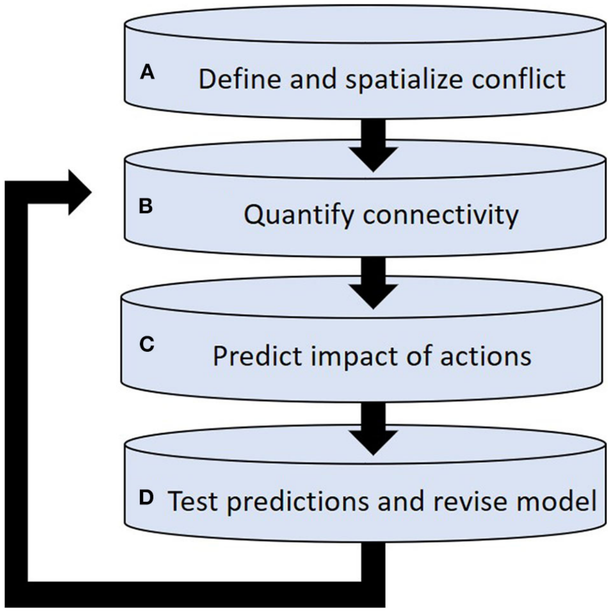

FIGURE 1 | Conceptual framework of adaptive management proposed to mitigate human-wildlife conflicts based on four steps: **(A)** define and spatialize conflict areas by considering social tolerance and negative interactions between human and wildlife at local scale; **(B)** predict animal distribution from empirical models of functional connectivity and patch residency time; **(C)** use advection-diffusion equations developed from functional connectivity models to predict the impact of management actions on animal distribution; and **(D)** test predictions in the field and revise the model as more information become available.

Hence, the level of HWC strongly depends on the tolerance of people toward wildlife (Ripple et al., 2014). This has led to the concept of social carrying capacity—the maximum wildlife population size that people are willing to tolerate (Cherry et al., 2019)—as well as to conflict-tolerance models (Kansky et al., 2016).

HWCs are unlikely to be uniformly distributed because landscape use by people and by wildlife generally displays spatial patterns at multiple scales. How often and where conflicts occur are partly determined by variation in environmental factors like resource distribution, agricultural practices, human occupation of land, and habitat connectivity (Mumby and Plotnik, 2018). Moreover, the presence a given behavior of animals may not be recognized and appreciated similarly by all people (Conforti and de Azevedo, 2003). Stakeholders may react differently to a given situation; for example, only some land owners give hunters access to their land (Simon and Fortin, 2019). Such differences exacerbate spatial heterogeneity in HWC. Defining HWC should therefore involve comprehensive assessment of the local situation, and locally acceptable levels should become management targets over local landscapes. A critical step in gaining insights into efficient organization of mitigation measures is therefore to spatialize conflict intensity, while considering patterns of negative interaction of wildlife with people and of social tolerance (Goswami et al., 2015; Kubasiewicz et al., 2016; Goswami and Vasudev, 2017).

PREDICT ANIMAL DISTRIBUTION FROM FUNCTIONAL CONNECTIVITY AND PATCH RESIDENCY TIME

Where a conflict zone is only a portion of an individual's home range, managers are required to know what principles govern movement into conflict areas. They need this information to identify effective and efficient mitigation measures. Movement decisions are linked to landscape connectivity which involves structural and functional components. Structural connectivity relates to the spatial configuration of patches in the landscape, whereas functional connectivity relates to how animals move between patches (Baguette and Van Dyck, 2007). Functional connectivity is species-specific and is considered fundamental to landscape connectivity (Mimet et al., 2013).

Network theory can be used to determine the changes in landscape connectivity following a disturbance or a management practice. In spatial ecology, a network is comprised of nodes (high-quality patches) connected by links (inter-patch movements) (Fall et al., 2007). Many studies have emphasized the value of using a network-theory framework to assess landscape connectivity in the context of conservation and management planning (Minor and Urban, 2008; Urban et al., 2009). For example, the effects of disturbance of patches or links can vary among networks depending on topology (Urban and Keitt, 2001; Fortuna et al., 2006; Prima et al., 2019). Management actions may target different network components to achieve animal distributions that can reduce HWC.

In addition to network topology and associated functional connectivity, the time that animals spend in individual patches defines the spatial dynamics of animal distribution (Bastille-Rousseau et al., 2010; Stehfest et al., 2015). Non-random movements among network patches and residency time can be considered through the creation of weighted networks (Urban and Keitt, 2001; Prima et al., 2018, 2019), whereby each link in every direction is assigned a relative probability of being used, and each patch is given a residency time.

Weighted Network

Elements of spatial networks can be weighted based on field observations to reflect how long an animal will remain in a given patch and which patch will be visited next. Various methods have been used to quantify these elements in the field. For example, residency time has been determined by setting cameras in resource patches (Courant and Fortin, 2012), whereas, interpatch movements have been identified by mapping trail networks with GPS units (Dancose et al., 2011). Global Positioning System (GPS) radio-collars are now widely used to track wildlife with increasing accuracy and frequency of relocations. Such advancements in animal monitoring provides the opportunity to quantify both patch residency time and interpatch movement.

Residency Times

Residency times in individual patches is now commonly quantified by considering parts of the movement segments entering and leaving a patch, together with the numbers of successive locations inside the patch [see Figure 1 of Bastille-Rousseau et al. (2011) for an example of residency time calculation]. The time spent in different patches can then be related to habitat features to identify determinants of residency time. A statistical method called "Cox Proportional Hazards" model has been used to identify habitat features that can explain the relative risk that an animal leaves its current patch at any point in time (Bastille-Rousseau et al., 2011; Courbin et al., 2014). Not surprisingly, for example, bison (*Bison bison*) have a lower "risk" or probability of leaving a meadow at a given point in time when they have access to higher biomass of highly profitable vegetation (Courant and Fortin, 2012). Alternatively, Prima et al. (2018) used multiple linear regression to quantify the relationship between residency time in resource patches to patch size, and then considered this information as one of the inputs to model animal distribution.

Interpatch Movements

GPS tracking collars can also be used to determine the sequence of patches that are visited in a network (Dancose et al., 2011; Courbin et al., 2014; Merkle et al., 2015), and then identify factors influencing interpatch movements. Habitat properties that make it more likely that an animal moves to and selects a particular patch can be identified based on matched case-control design (Duchesne et al., 2010; Courbin et al., 2014; Merkle et al., 2014). The approach creates strata, with each stratum including a link (a potential interpatch movement) that was actually traveled by the collared animal (observed link, scored 1) and a set of links that could have been traveled from the same initial patch (random link, scored 0). Habitat features associated with traveled and available links are then contrasted based on conditional logistic regression (Compton et al., 2002). Patterned after step-selection functions (SSFs, Fortin et al., 2005) and in the context of HWC, the statistical model describing inter-patch movements can take the general form:

$$\hat{w} = exp(\beta_L L_L + \beta_D cos[\phi] D^C + \beta_1 x_1 + \ldots + \beta_p x_p). \qquad (1)$$

where $\hat{w}$ is the model's score, βs are regression coefficients, L_L is the link length [Euclidean or functional distance of the interpatch movement, Courbin et al. (2014) and Tardy et al. (2018)], ϕ is the angle difference between the direction of an observed or random link and that of the nearest conflict zone (**Figure 2**), D is the Euclidean distance to the conflict zone (**Figure 2**), and C is a parameter that allows the consideration of how the animal adjusts its movement with respect to the targeted patch (conflict zone) as a function of its distance to that patch. D^C thus enables the model to consider that an animal may display stronger directional movement (cos[ϕ]) as it gets closer to the target (Bartoń et al., 2009). Covariates x_1 to x_p can represent a broad range of factors that influence movement decisions, such as movement taxis in response to various stimuli (Dancose et al., 2011; Latombe et al., 2014b; Nicosia et al., 2017) or selection of habitat features located either along the link leading to the next patch or associated directly with the location of that patch (Courbin et al., 2014; Merkle et al., 2014, 2015). For example, bison move toward canopy gaps when they travel in a forest, a behavior that has been revealed by estimating an SSF that included the cosine of the angle difference between the direction of observed or random interpatch movements and that of the nearest canopy gap (Dancose et al., 2011). Covariates can also include measurements such as the minimum distance to a particular habitat feature (e.g., nearest road), proportion of the link consisting of a particular land cover type (e.g., conifer forest, lake), expected energy requirement to reach the patch, and predation risk at the arrival patch (Fortin et al., 2005). Once parameters are estimated, Equation (1) can be used to assign weights to the links of the spatial network. The relative probability that the animal leaving patch j reaches patch i among the m patches that can be reached from its current location is given by:

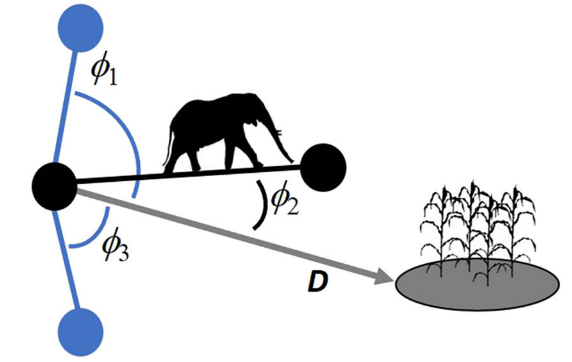

FIGURE 2 | Example of observed (black to black patch) and potential (black to blue patch) interpatch movements, with associated measurements for the difference between the direction of an interpatch movement and the nearest conflict zone (ϕ_i, where ϕ_1 and ϕ_3 are associated with untraveled but available interpatch movements and ϕ_2 is associated with the observed movement), and the Euclidean distance to the conflict zone (*D*).

$$a_{ji} = \frac{\hat{w}_{ji}}{\sum_{i=1}^{m} \hat{w}_{ji}} \; \forall j, i = 1, \ldots, m, \; j \neq i \qquad (2)$$

Probabilities of all m potential interpatch movements thus sum up to 1 (see, e.g., $m = 5$ around each black patch in **Figure 3**). Available patches can be identified from field observations (O'Brien et al., 2006; Courbin et al., 2014; Prima et al., 2019).

Quantification of a_{ji} for the different links of a network can inform on the challenges and opportunities of reducing the risk of HWC. For example, consider a spatial network within which three patches have the same patterns of structural connectivity with respect to their adjacent patches (**Figure 3A**). We assume that the relative probability that an animal leaves one of the three patches to reach an adjacent patch follows:

$$\hat{w}_{ji} = \exp(-0.5\, L_{Lji} + 1.2\, D_{ji}{}^{-0.5} cos[\phi_{ji}]) \qquad (3)$$

Given this movement rule, the three patches display differences in functional connectivity despite having the same structural

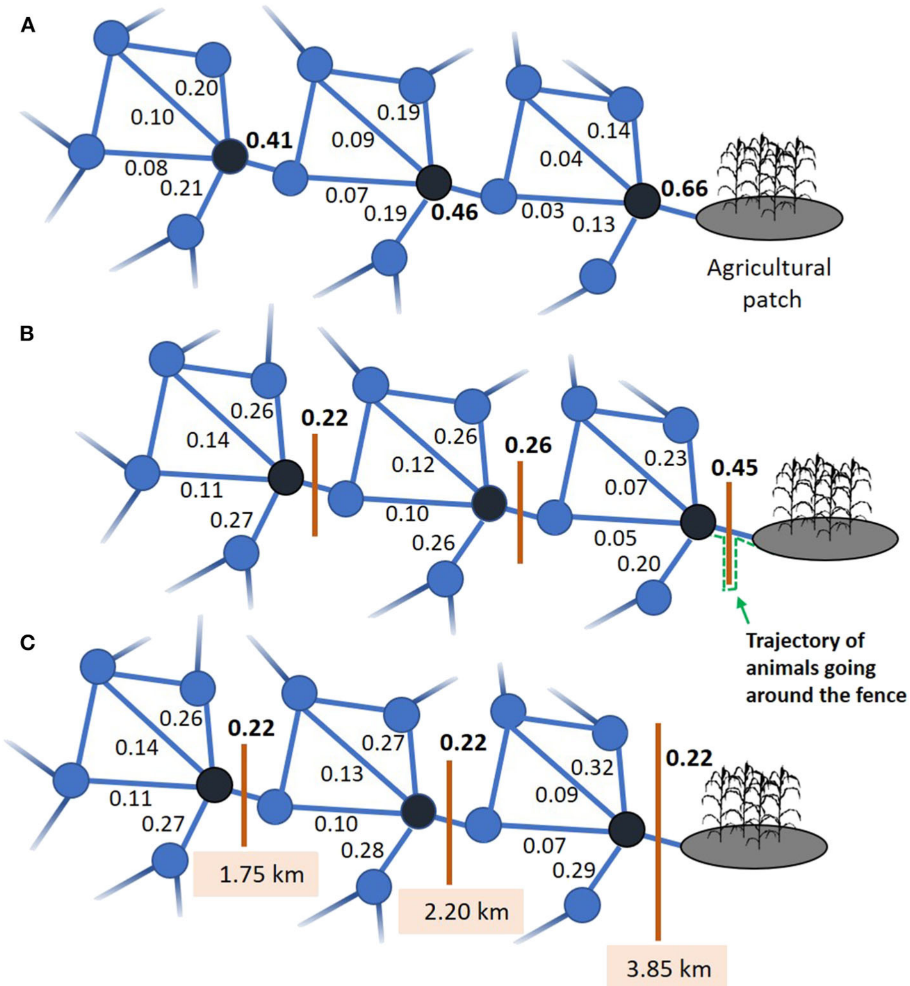

FIGURE 3 | (A) Subset of a trail network showing the relative probability of traveling from the three black patches to each of the five connected patches, as estimated from Equation (3). **(B)** Outcome on the relative probability of traveling the different trails from the black nodes, following the erection of fences (orange lines). The 1.75-km fences intersect the edges between two patches that are 1.1 km apart, which imposes a 2.85-km path for an animal traveling between them while going around the fence, as illustrated by the dotted green line. **(C)** Fence lengths (1.75, 2.20, and 3.85 km) required to maintain a probability of 0.22 that the animal travels between the two patches by going around the fence, given that movement taxis intensifies with proximity to the agricultural patch.

connectivity. This is because the attraction of animals toward the agricultural patch increases in intensity as they get closer (i.e., 1.2 $D^{-0.5}$ $cos[\phi]$). Such distance-dependent responses to habitat features have been reported for multiple species (McClintock et al., 2012; Preisler et al., 2013; Latombe et al., 2014a). To illustrate the calculation, let us consider the link between the nearest black node and the agricultural patch (**Figure 3A**). Following Equation (3), we can estimate $\hat{w} = \exp(-0.5 \times 1.1\,\text{km} + 1.2 \times 1.1^{-0.5} \times \cos[10°])$ $= 1.78$. After estimating $\hat{w}_{ji}$ for each of the other four connected patches, we can calculate a (Equation 2) for the link specifically leading to the agricultural patch as 1.78 / (0.08 + 0.11 + 0.37 + 0.33 + 1.78) = 0.66. More globally, a_{ji} values associated with the links leading the agricultural patch varied between 41 and 66% for all three hubs (black patches, **Figure 3A**).

Relative Use of Patch Network Given Movement Rules

Once the determinants of residency time and interpatch movement have been identified and their impact quantified, these elements of landscape connectivity can then be used to infer the relative distribution of individuals in the network. To do so, an advection-reaction-diffusion model can be used with predictions of animal distribution being proportional to relative intensity of space use (Prima et al., 2018). Consider the following reaction-diffusion model applied to a network with N patches:

$$\frac{d\boldsymbol{U}(\boldsymbol{t})}{dt} = \boldsymbol{F}(\boldsymbol{U}\,(\boldsymbol{t})\,)+\boldsymbol{G}(\boldsymbol{U}\,(\boldsymbol{t})\,) \tag{4}$$

where $\boldsymbol{U}(\boldsymbol{t}) = [u_1(t), u_2(t),\ldots, u_N(t)]^T$ is the vector of animal densities at time t in the N patches of the network, $\frac{d\boldsymbol{U}(t)}{dt}$ is the vector of instantaneous rate of change in $\boldsymbol{U}\,(\boldsymbol{t})$,

$\boldsymbol{F} = [f_1(\boldsymbol{U}(\boldsymbol{t})), f_2(\boldsymbol{U}(\boldsymbol{t})), \ldots, f_N(\boldsymbol{U}(\boldsymbol{t}))]^T$ is the vector of reaction functions in the N patches of the network and $\boldsymbol{G} = [g_1(\boldsymbol{U}(\boldsymbol{t})), g_2(\boldsymbol{U}(\boldsymbol{t})), \ldots, g_N(\boldsymbol{U}(\boldsymbol{t}))]^T$ is the vector of diffusion functions in the N patches of the network (Kouvaris et al., 2012). The reaction term can be modeled as the density of individuals leaving patch i, based upon residency time in patch i:

$$f_i(\boldsymbol{U}(\boldsymbol{t})) = -\frac{u_i(t)}{T_i},\ i \in \{1, \ldots, N\}, \tag{5}$$

where T_i is the average residency time in patch i. A higher residency time in patch i is reflected by a lower number of individuals leaving patch i. Advection properties can be modeled by assigning weights to the network's links, which then reflects an uneven movement of individuals between connected network patches. The advection process then can be implemented by modifying the diffusion term to:

$$g_i\left(\boldsymbol{U}(\boldsymbol{t})\right) = \sum_{j=1}^{N} a_{ji}\frac{u_j(t)}{T_j},\ i \in \{1, \ldots, N\}, \tag{6}$$

where a_{ji} (Equation 2) which is proportional to the number of individuals arriving to patch i. Equation (4) becomes:

$$\frac{\boldsymbol{dU}\,(\boldsymbol{t})}{\boldsymbol{dt}} = \left(\boldsymbol{A}^{\boldsymbol{T}} - \boldsymbol{I}\right)\boldsymbol{T}^{-1}\boldsymbol{U}\,(\boldsymbol{t}), \tag{7}$$

where $\boldsymbol{I}$ is the identity matrix, $\boldsymbol{A}$ is the weighted adjacency matrix of the network containing all weights $a_{ij}, i, j \in \{1, \ldots, N\}^2$, and $\boldsymbol{T}$ is a diagonal matrix of the residency times in the N nodes of the network. Predicted densities at any time of the simulation can be transformed to estimate relative intensity of space use:

$$I_i(t) = \frac{u_i(t)}{\sum_{j=1}^{N} u_j(t)} \tag{8}$$

where $I_i(t)$ is the relative intensity of use for node i at time t.

To illustrate the relationship among functional connectivity, patch residency time and animal distribution dynamics, we created a fictive network of 50 natural resource patches and two human-related patches (agricultural patches 51 and 52) where HWC can occur (**Figure 4A**). We assume that animals display the same residency time (5 time units) in every patch, and inter-patch movements follows:

$$\hat{w}_{ji} = exp(-3\ L_{Lji} + 0.1\ D_{ji}^{-0.1} cos[\phi_{ji}]) \tag{9}$$

Accordingly, animals are less likely to transit to a distant than nearby patch ($\beta_L < 0$), and they are more likely to aim toward than away from the nearest agricultural patch ($\beta_D > 0$), especially as they get closer to that patch ($C < 0$). We start the simulation with 10 individuals in each of the 52 patches and solve the system numerically to estimate the stable state solution, as described by Prima et al. (2018). In the context of adaptive management, transient distribution states might be of interest, which would simply require keeping track of how the system develops during its numerical resolution. In this case, initial conditions should impact how the system behave over time before reaching its steady state. An insightful approach could then be to set initial conditions to reflect animal distribution that creates human-wildlife conflicts. Here we simply focus on the steady-state solution.

Under these rules and once the steady-state is reached, we observe a directed network with a general gradient of increasing use toward the two agricultural patches (**Figure 4A**). The most heavily used patches, however, are not the two agricultural ones, which demonstrates the role of structural connectivity such as the node's degree (number of links).

PREDICTING IMPACTS OF MANAGEMENT ACTIONS

Once the relative use of resource patches within the network can be anticipated from basic movement rules, the predictive model can be used to anticipate the outcome management actions on the risk of HWC. Conflicts can be mitigated using a large set of potential interventions (Miller et al., 2016; Nyhus, 2016; Ravenelle and Nyhus, 2017; König et al., 2020). For example, wildlife authorities may disturb and chase problem animals out of sensitive areas. Managers can even benefit from early warning by fitting individuals with collars that relay information over the mobile telephone network when collared-animals enter a sensitive zone (Graham et al., 2012). Managers may install olfactory (e.g., the use of *Capsicum* spp. as barrier plants), acoustic (e.g., drones, sirens, firecrackers) and visual (e.g., flashing light) deterrents, some of which can be activated by motion sensors (Blackwell et al., 2016; Miller et al., 2016; Enukwa, 2017). Beehive fences can prevent the use of some areas by African elephants (*Loxodonta africana*), while also providing farmers with financial benefit through honey production (Enukwa, 2017). Virtual fencing can be deployed with shock collars that are triggered when collared animals reach a virtual boundary (Miller et al., 2016; Campbell et al., 2019). Chacma baboons (*Papio ursinus*) cause damage to both crops and human infrastructure in South Africa, and virtual fences have been used with varying levels of success to redirect baboons away from human settlement (Kaplan and O'Riain, 2014). The use of biofences to control predators has had some success, with constant reapplication of urine and feces (Ausband et al., 2013). Although the use of fences has been questioned (Pfeifer et al., 2014; Woodroffe et al., 2014), their use remains a classic means to restrict movements toward areas prone to HWC. When an area is not entirely fenced, animals can circumvent fences (Meagher, 1989; Hoare, 2012). Even then, the longer travel distance required by going around a fence should decrease the probability of making this interpatch movement because inter-patch movements become less likely with increasing travel distances (Dancose et al., 2011; Courbin et al., 2014; Tardy et al., 2018).

To illustrate how management actions can be tailored to movement rules within the patch network, we can go back to the example displayed in **Figure 3**. In this case, the probability

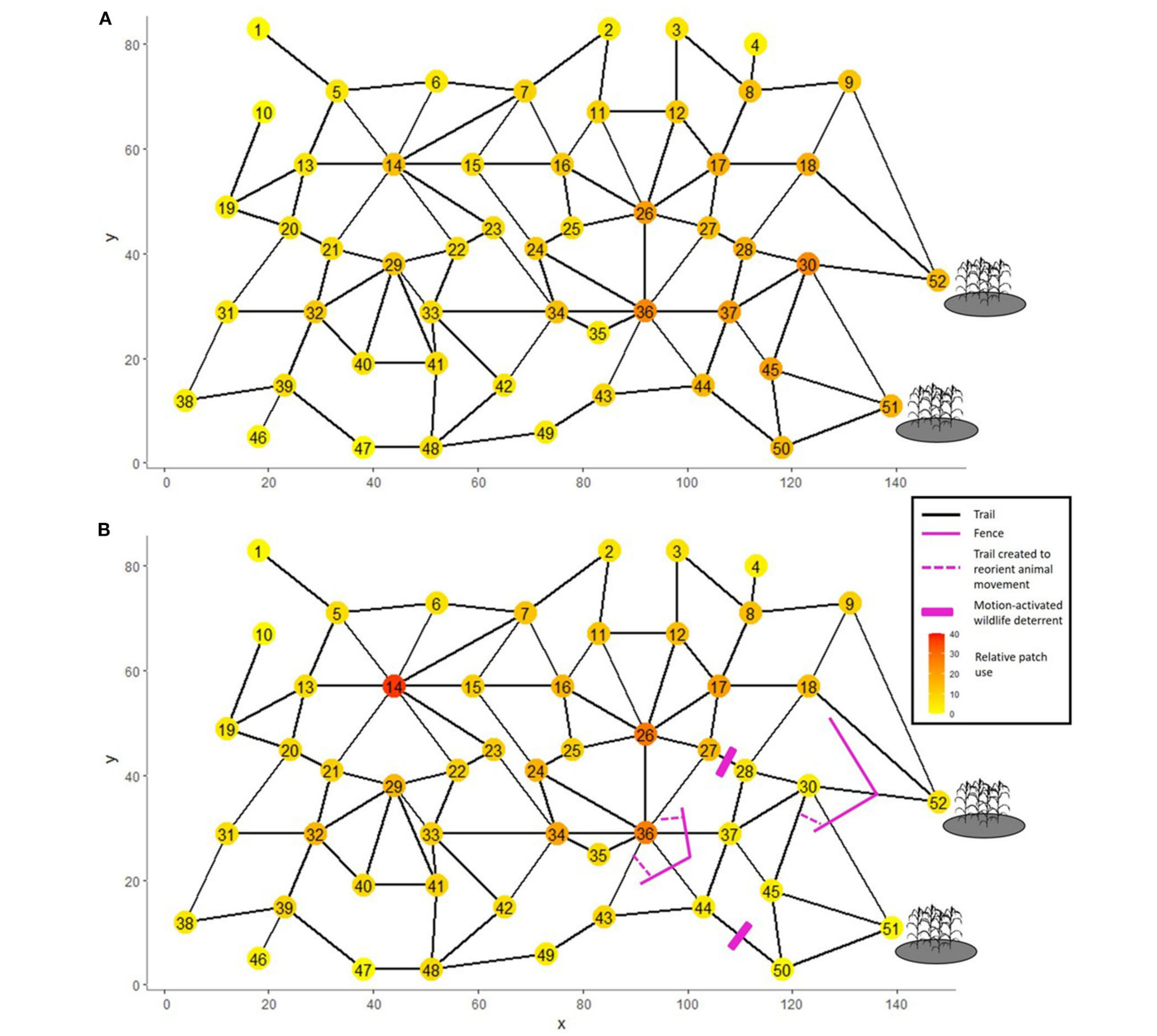

FIGURE 4 | Hypothetical spatial network comprised of 52 patches—including two agricultural patches where human-wildlife conflicts occur—connected by links (trails) with relative probability of travel given by Equation (9). **(A)** Relative patch use before any management intervention. **(B)** Relative patch use following five types of interventions: erecting fences, crating trails to reorient animal traveling along a fence, deploying motion-activated wildlife deterrent, adding resources in patch 14, and disturbing of animals to reduce their residency times in patches 51 and 52.

of interpatch movement not only depends on travel distance, but also on the level of attraction of the nearest agricultural patch which increases as individuals get closer to this target. Such distance-dependent, directional movement implies that a given management action becomes less likely to be effective as animals approach the conflict zone. Let us assume that 1.75-km fences are set to impede movement toward the agricultural patch. Individuals can go around the fence by traveling 2.85 km (i.e., [0.55 km to travel the first half the trail length] + [1.75 km to walk to the end of the fence and then to walk back to the trail on the other side of the fence] + [0.55 km to travel the second half of the trail length = 2.85 km], **Figure 3B**), a distance that would reduce the likelihood of making that step following Equation (3) (**Figure 3B**). Indeed, L_{Lji} in Equation (3) will take a value of 2.85 with the fence, instead of 1.1 km without a fence. On this basis, we can estimate that animals would be twice as likely to move around the fence located the nearest than the farthest from the conflict zone (Equation 3). In fact, to maintain the same probability of traveling for all three focal nodes (black patches) the fence would need to gradually increase from 1.75 to 3.85 km (**Figure 3C**).

We now consider the more complex example displayed in **Figure 4**. Let us assume that we deploy four types of intervention in the patch network, each with different expected consequences on the response of large herbivores. This would be the case of bison, for example, living in a forest environment (e.g., landscape is displayed in Babin et al., 2011) adjacent to agricultural lands and traveling within a trail network (see illustrations in Dancose et al., 2011). The spatial distribution of management interventions can be decided based on various indices of landscape connectivity (e.g., betweenness centrality, Perry et al., 2017). Here we orient our decision from a visual inspection of network structure, as identified from greedy optimization of modularity (Clauset et al., 2004). We detected five network communities (sensu Cai et al., 2020) for which potential movements involve stronger interconnection among patches within than between communities. On this basis, we reduced movement toward the community involving the agricultural patches, while promoting movement out of that community. Specifically, we assume that a fence was erected with a design that prevents movements from 36 to 37 and 44, but not from 37 or 44 to 36 (**Figure 4B**). Another (virtual) fence was placed to prevent movement from 30 to 51 and 52. The fence configuration is expected, however, to reduce movement from 51 to 30 by decreasing $\hat{w}_{51,30}$ by 50% (i.e., $\exp[-3\ L_L + 0.1\ D^{-0.1}\ cos(\phi_F)] \times 0.5$), and to increase movement from 52 to 18 by $\hat{w}_{52,18} \times 125\%$. We assume that a motion-activated wildlife deterrent (e.g., radio speaker) was installed along trails pointing away from patches 28 and 50 (**Figure 4B**), such that animals do not travel from 27 to 28 or from 44 to 50, but can still travel from 28 to 27 and from 50 to 44. We further assume that the addition of resources (food and/or water) double residency time in patch 14, whereas the disturbance of individuals (e.g., hazing) reduce their residency times in patches 51 and 52 from 5 to 4 time units. To assess the impact of these interventions on expected animal distribution, we start the simulation with 10 individuals in each of the 52 patches and solve the system numerically to estimate the stable state solution given these local changes in movement rules.

Before these interventions the two agricultural patches (51, 52) had 30.6 individuals (5.9% of the population) at equilibrium, which declined to 7.3 (1.4%) after the application of all these interventions (**Figure 4B**—remember that animal number is proportional to relative intensity of space use). If we remove a single intervention, we find that increasing residency time in patch 14 by adding resources had the least impact on the use of agricultural patches, whereas removing the fence between 36 and 37 and 44 had the largest impact (**Figure 5**). By contrast, if we implement a single intervention, we find that increasing residency time in patch 14 resulted in the lowest decrease in the use of the two agricultural patches, whereas erecting the fence between 30 and 51 and 52 had the largest impact. The lack of symmetry between the impact of implementing and removing a single intervention (**Figure 5**) illustrates that the effect of interventions cannot be expected to be simply additive to one another. A holistic assessment of management plans should therefore be carried out to identify the most effective strategy. As we show, the proposed analytical approach can provide such global assessment of multiple interventions altogether.

TEST PREDICTIONS AND REVISE MODEL

The implementation of management plans needs to be monitored for several reasons. For example, multiple species may be simultaneously impacted by local interventions. Monitoring is required to ensure that mitigation measures aimed at reducing a given HWC does not jeopardize other conservation or management objectives (Jordán and Báldi, 2013; Sigaud et al., 2020). Also, wildlife management is often driven by the immediate need to solve a problem (Blackwell et al., 2016), such actions may have to precede the development of a mitigation plan based on an exhaustive understanding the behaviors resulting in HWC. The choice of mitigation measures thus may be based on observations conducted on other species, on few observations of the system or an educated guess. Even highly detailed observations collected over short-term period are unlikely fully to capture all behavioral decisions causing HWC. This can be due, for example, to seasonal variations in animal-habitat relationships. In Canada bison typically only leave the safety of a national park (i.e., Prince Albert National Park) between mid-summer and mid-fall, when highly profitable vegetation is abundant in agricultural fields (Sigaud et al., 2017, 2020). Wild boar (*Sus scrofa*) in Alta Murgia National Park, Italy, thrive on natural vegetation during much of the year, and only switch to cultivated crops during summer (Ficetola et al., 2014). In Zimbabwe, African elephants switched to crop raiding toward the end of the wet season when grass quality in protected areas begin to decrease (Osborn, 2004). Both plant-herbivore and predator-prey interactions vary dynamically during the course of the year (Babin et al., 2011; Simon et al., 2019), such that movement decisions and related functional connectivity can also change.

The effectiveness of mitigation measures may also change over time. For biofencing to work, for example, urine and feces need to be frequently reapplied (Ausband et al., 2013). Monitoring is thus needed to determine how long each application maintains its effectiveness given the species involved and local environmental conditions. Management techniques also differ in how long they remain effective. Acoustic deterrents appear to impact carnivores/omnivores for only a few days, whereas shock collars can maintain their effectiveness for over a year (Miller et al., 2016). Given uncertainty in the effectiveness of actions, management plans can be improved over time by using an adaptive approach (Walters and Hilborn, 1978; Richardson et al., 2020). Information gathered by monitoring the response of animals to the management actions should thus be used to refine the predictive model (**Figure 1**), and adjust the mitigation plan over time to improve or maintain its efficiency and effectiveness.

DISCUSSION

The need for effective HWC mitigation is more important now than ever, as across the globe humans and wildlife increasingly compete for space and resources. We present an adaptive

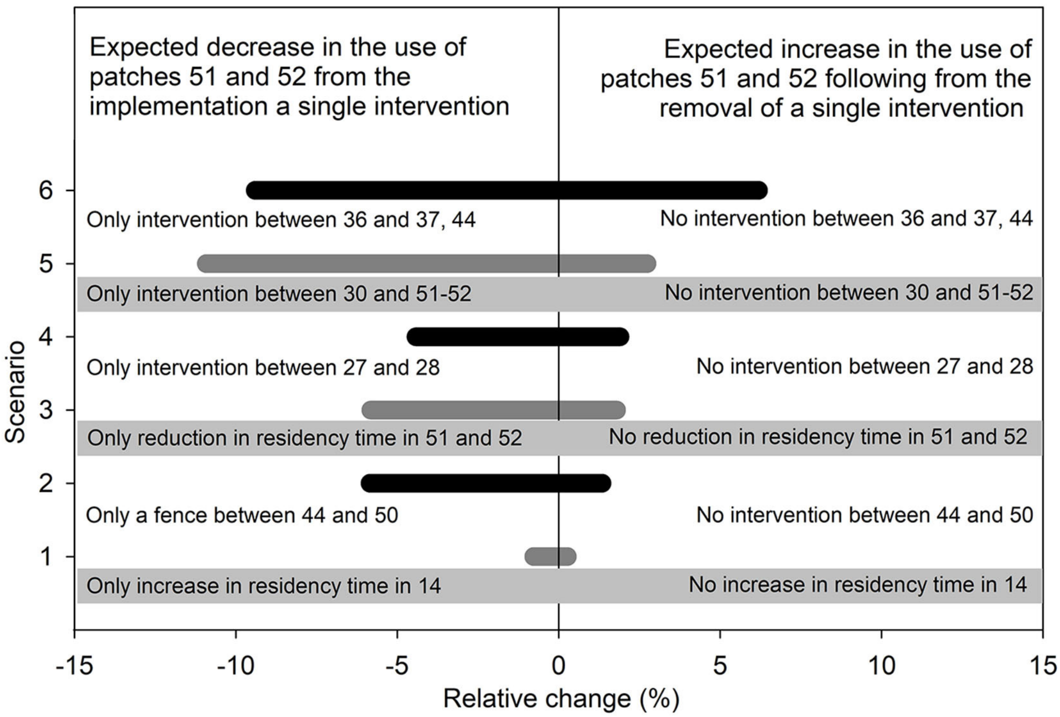

FIGURE 5 | Predicted impact of implementing a single intervention among those displayed in **Figure 4B** on the combined use of the two agricultural patches displayed in **Figure 4A**, together with predicted impact of removing a single intervention among those displayed in **Figure 4B** on the combined use of the two agricultural patches displayed in **Figure 4B**. The text on gray background refers to the gray bars, where the text on the white background refers to the black bars.

management framework that involves the use of quantitative ecology to strategically alter the movement and distribution of animals in a way that reduces HWC. A fundamental principle is that animal movement can be characterized across the landscape, including along the main paths used to reach areas prone to HWC, and this information is then used to identify the most effective HWC mitigation strategies.

Although we specify that our examples could reflect a situation where bison might travel among well-delineated meadow patches in a forest matrix, the proposed framework is more broadly applicable. Our framework is suitable when animal movements can be predicted within a patch network. For example, a network approach was used to clarify the link between habitat changes and landscape connectivity for species ranging from small frogs (Schivo et al., 2020) to African elephants (Bastille-Rousseau and Wittemyer, 2020). As with these studies, our framework involves knowledge of how animals adjust their interpatch movements in response to landscape changes; however, here we suggest to actively manipulate landscape features to alter inter-patch functional connectivity in a way that results in suitable management or conservation outcomes.

Relevant spatial networks may be developed based on various patch types. Past studies have built network while considering, for instance, that nodes (patches) were water holes (Heintzman and McIntyre, 2019), discrete meadows (Prima et al., 2018), stands of deciduous vegetation (Courbin et al., 2014), or large stands of conifer vegetation (Prima et al., 2019). A patch is often a resource-rich area or a landcover type that is selectively used by the animal. The network of two species may thus be organized around different patch types, even if both species are established in the same landscape (Courbin et al., 2014). When habitat patches are difficult to circumscribe (e.g., less discrete systems), habitat selection analysis can provide guidance. O'Brien et al. (2006), for example, analyse habitat selection by woodland caribou (*Rangifer tarandus caribou*), and used the results to develop a spatial network for which high-quality patches were comprised of mature jack pine stands and sparsely treed rock. Movement among those patches then becomes the basis to define structural landscape connectivity.

Managers develop strategies for conservation while considering that the intensity and spatial patterns of HWC can be highly dynamic. For example, information sharing among animals can lead to a steep increase in HWC, with problematic behaviors becoming the norm within a few years (Sigaud et al., 2017). Also, the presence of animals on private lands may be undesirable only during a portion of the year, such as when wildlife might interact with domestic animals or when damage to property is most likely. Management may then involve interventions deployed specifically where and when the level of social tolerance toward wildlife is exceeded. In this context, public outreach programs and monetary compensation for wildlife damage may be used to reduce HWC by increasing social tolerance (Ravenelle and Nyhus, 2017). Conservation agencies may also purchase lands with high HWC or where managers can attract wildlife to lessen HWC elsewhere (Curran et al., 2016; Sijtsma et al., 2020).

Management strategies should be developed while considering that interventions can have consequences well-beyond the target population or the conflict areas (Osipova et al., 2018; Sigaud et al., 2020). Efforts to protect a given population may even conflict with the conservation objectives of other populations (Williams et al., 2011; Baynham-Herd et al., 2018). Increasing social tolerance can certainly reduce HWC with minimal impact on wildlife species and their habitat. Here we propose to make management plans based on strategically placed interventions, so that managers can pinpoint where HWC mitigation measures would be most effective with the least impact on animals not involved in conflicts. Accordingly, assessing the interplay between animal movement and landscape features should be done while considering that different population members may use different movement tactics. For example, males and females of a given species do not use the landscape similarly (e.g., Bjorneraas et al., 2012; Marchand et al., 2015; Paton et al., 2017), and in the case of the African elephant, males are more frequently involved in HWC (Cook et al., 2015; Orrick, 2018). Even individuals of the same sex of may display different tactics (Dussault et al., 2012; Losier et al., 2015), with some being more likely to trigger HWC (Sigaud et al., 2017). To be most effective and minimize the impact on non-problem animals, functional connectivity can be quantified concurrently for population members with different movement tactics and for other species (e.g., Courbin et al., 2014); the expected impact of management can then be assessed broadly for community members based on the proposed framework.

Our study demonstrates how quantitative ecology can help understand spatio-temporal patterns of animal distribution, and provide a valuable basis to for the development of effective and efficient management strategies to mitigate HWC. By modeling HWC managers and conservationists can benefit from testing different scenarios before implementation, especially where non-target species are involved. We provide a method for "out of the box thinking" (Shivik, 2006; Blackwell et al., 2016) in line with the notion that fencing broad areas is not a panacea of HWC solving. As more options become available, our framework can provide guidance for the deployment of management actions to reduce conflicts to socially acceptable levels.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

DF: conceptualization, formal analysis, funding acquisition, methodology, wrote—original draft, wrote—review and editing. CB, PL, HF, PM, and OP: wrote—review and editing. All authors contributed to the article and approved the submitted version.

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Conservation Policies, Eco-Tourism, and End of Pastoralism in Indian Himalaya?

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State-led policies of pastoralist removal from protected areas, following the fortress model of biodiversity conservation, have been a common practice across parts of Asia and Africa. In the Himalayan region of South Asia, restrictive access and removal of pastoralist communities from protected areas have been compensated by the state through "eco"-tourism. In this paper, we critique the current conservation model adopted in the Indian Himalaya, which focuses on a conservation-pastoral eviction-ecotourism coupling. With a focus on pastoralists and pastoral practices, we argue that this model is neither an inclusive engine of development, nor does it always help conservation. Instead, it recreates a landscape favoring the state's interests, produces exclusions, and may also negatively affect both society and ecology. We build on the case of Khangchendzonga National Park (KNP) situated in Sikkim, Eastern Himalaya. We used mixed methods and conducted 48 semi-structured interviews, 10 key informant interviews, and two focused group discussion in the four village clusters situated in the vicinity of KNP, West Sikkim. The grazing ban policy and concomitant promotion of tourism caused the end of pastoralism in KNP. It transformed a pastoral cultural landscape into a tourist spot with a transition in livestock from the traditional herds of yak and sheep to the pack animals and non-native hybrid cattle. Locally perceived social impacts of the grazing ban include loss of pastoral culture, economic loss, and the exclusion of the pastoral community from the park. As per the respondents, perceived ecological effects include a decline in vegetation diversity in the high-altitude summer pastures, altered vegetation composition in the winter due to plantation of non-native tree species, and increased incidents of human-wildlife conflict. Rangelands of the Himalaya transcend political boundaries across countries. The conservation model in Himalaya, should henceforth be done with a trans-boundary level planning involving the prime users of high-altitude rangelands, i.e., the pastoralists. The lessons from this study can help design effective future policy interventions in landscapes critical for both pastoralist cultures and wildlife conservation.

Keywords: rangeland conservation, grazing ban, pastoral livelihood, eco-tourism, conservation policy, Khangchendzonga National Park, Himalaya

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INTRODUCTION

The conservation discourse on pastoral use of natural resources is replete with two polarized and opposing narratives. The first narrative looks at all forms of human land-use practices, especially pastoralism and agriculture as necessarily leading to degradation and a decline in biological diversity (Johnson, 1977; Briske and Richards, 1995; Beinart, 1996; Weber and Horst, 2011; Ren et al., 2012; Thapa et al., 2016; Wang and Wesche, 2016). Pastoralist communities are blamed for being responsible for the degradation of rangelands. This assumption follows the classical approach to the equilibrium model that assumes that rangeland ecosystems are potentially stable systems destabilized by pastoralist communities' improper use and overstocking of the rangelands (Stebbings, 1935; Brown, 1971). Based on this line of thought, conservationists often see humans' exclusion from areas of conservation interest as the only viable solution.

A contrasting line of thought emerged as a critique of the equilibrium paradigm, becoming widespread as "new rangeland ecology." Scholars of new rangeland ecology argued that the equilibrium model did not consider the social heterogeneity, climatic variability and the adaptive resource use by the pastoral communities (Behnke and Scoones, 1992; Scoones, 1994; Leach et al., 1999). They argued that pastoralists have co-existed with nature following their institutional systems embedded in the social and ecological heterogeneity (Scoones, 1994; Robbins, 1998; Berkes et al., 2007; Jun Li et al., 2007). These systems also constantly evolve in response to the local geo-climatic conditions, and ecological and social variabilities (Scoones, 1994; Mortimore, 1998; Mortimore and Turner, 2005; Butt, 2011; Haynes and Yang, 2013; Wu et al., 2014; Singh et al., 2015).

The debate on compatibility between grazing and pastoral resource use and conservation remains unsettled. However, the former view influenced conservation policies. It led to, curtailed access to pastures, sedentarization, and even removal of pastoralists communities from their traditional pastures across the pastoral landscapes of Asia and Africa (Behnke and Scoones, 1992; Mortimore, 1998; Yeh, 2005; Zhizhong and Wen, 2008; Gonin and Gautier, 2015; Schmidt and Pearson, 2016).

The high altitude region of Himalaya in South Asia is a multiuse landscape with a wide variety of pastoralist communities that includes agro-pastoralists, seminomadic, and transhuman system (Rao and Casimir, 1982; Bhasin, 2011; Yamaguchi, 2011; Kreutzmann, 2012; Namgay et al., 2013; Yeh et al., 2017), as well-being a critical landscape for wildlife conservation with its unique assemblage of wild ungulates and carnivores (Mishra et al., 1998). Resource sharing by livestock and wildlife in the region, especially in the Trans-Himalaya, is often seen as being in conflict with the conservation efforts (Fernandez-Gimenez and Allen-Diaz, 1999; Kala, 2005; Sangay and Vernes, 2008; Shrestha and Wegge, 2008; Suryawanshi et al., 2010; Bagchi et al., 2012; Berger et al., 2013; Namgay et al., 2013; Ashraf et al., 2014), with very few exceptions of coexistence (Bhatnagar, 2009; Sharma et al., 2015).

The generalization that rangelands degradation occurs due to pastoral resource use resulted in multiple policies for pastoral restrictions in protected areas and physical evictions of pastoral communities from several states of Indian Himalaya. Nanda Devi National Park (Nautiyal et al., 2003) the Valley of Flowers National Park (Rawat and Uniyal, 1993; Kala, 2005; Gairola et al., 2015) in Uttarakhand, and Greater Himalaya National Park of Himachal Pradesh (Mehra and Mathur, 2001; Chhatre and Saberwal, 2005, 2006) are some of the examples of ostensibly science-based policymaking. What is striking is that ecotourism has been the state's solution to the conservation conflict in each of these landscapes. Ecotourism in the region has been promoted by the state and agencies, such as the World Bank as an alternative to fortress conservation and a win-win solution capable of meeting both conservation and community development goals.

The State of Sikkim, in the Eastern Himalaya of India, implemented a ban on livestock grazing inside protected areas in the year 1998. Pastoralists who have been living and herding yaks, sheep and cattle inside the protected area were no longer allowed to herd their animals in the national parks and sanctuaries of Sikkim. Protected areas across Sikkim witnessed massive physical evictions of pastoralists between the year 2000–2002. In 2002, the state government constituted eco-development committees around the protected areas to implement a range of eco-development and ecotourism practices. The grazing ban, followed by pastoral removal and implementation of eco-development committees, followed the similar chain of events that have become a part of the Himalayan region's conservation model.

In this paper, we argue that the current conservation model, implemented in the Himalayan states with the restrictive conservation policies, pastoral eviction and ecotourism coupling, is neither an inclusive model of development nor is it embedded in the local socio-ecological needs for conservation. Using the case study of Khangchendzonga National Park (KNP), West Sikkim, we show how it entails a massive social cost, particularly for pastoral livelihoods, and results in elite capture, with no guarantee of ecological benefits. To support our argument, we draw upon the empirical data on four village clusters in the vicinity of KNP, West Sikkim gathered between the year 2017–2019. This study aimed to understand the influence of the conservation-pastoral eviction-ecotourism coupling on the pastoral system in KNP. Specific objectives were to (1) document the long term change in the traditional pastoral livelihoods and livestock composition in the KNP region, (2) Examine the influence of two key events *viz.* advent of tourism and ban on livestock grazing on pastoralism, and (3) Understand the locally perceived ecological and social influence of the resultant transition, primarily for the landscape and the local community.

STUDY AREA

This study was conducted in four village clusters of West Sikkim situated at the periphery of the Khangchendzonga National Park (KNP) (**Figure 1**). These four village clusters *viz.* Yuksam, Darap, Uttarey, and Karzi lie at the intersection of the questions that we explore in this paper. These were the most important village clusters for pastoral practices in West Sikkim and were the most

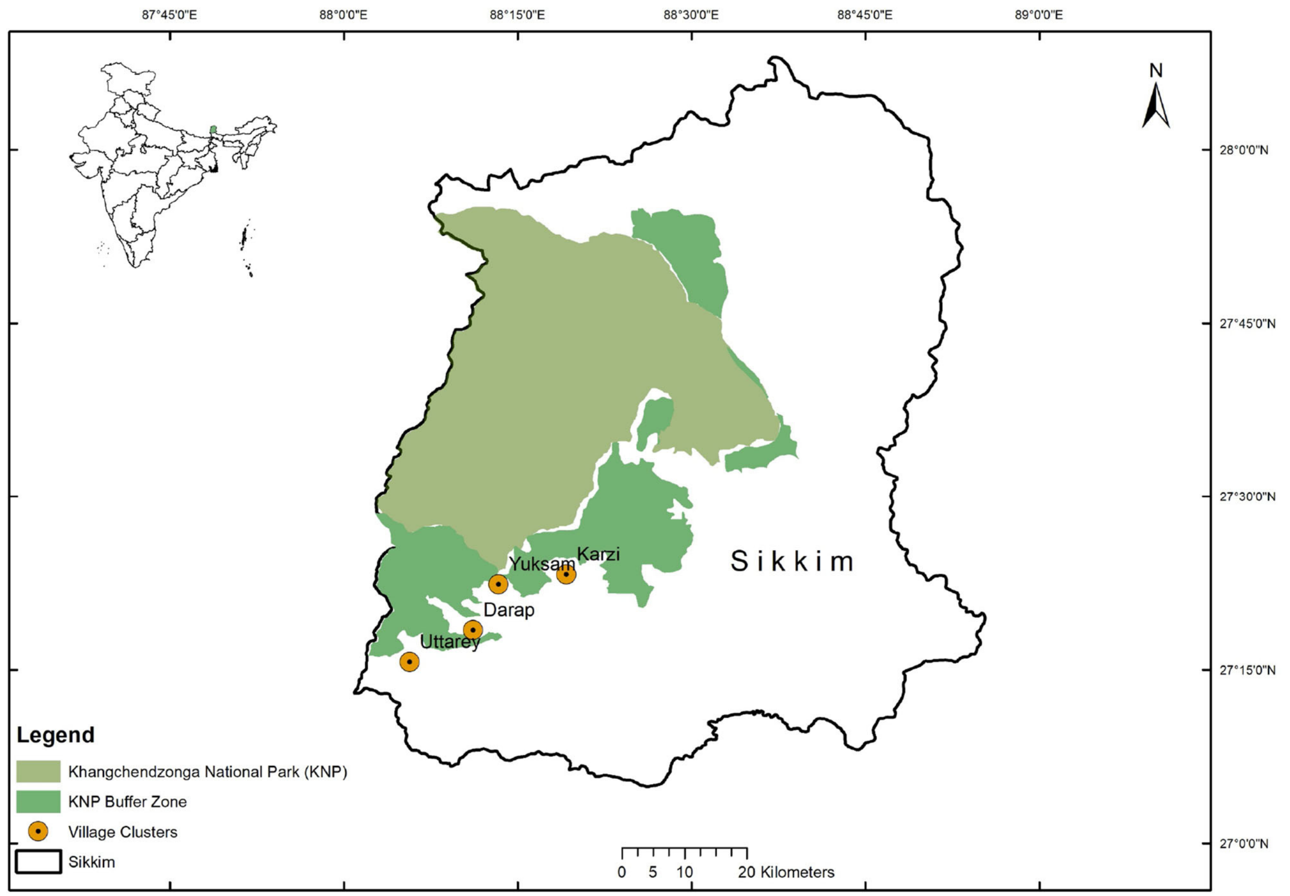

FIGURE 1 | Map highlighting Khangchendzonga National Park (KNP) and the location of four village clusters in the study area.

affected by the grazing ban. KNP covers an area of 1,784 sq. km. The State of Sikkim is located in the Eastern Himalaya of India. The state is 7,096 km^2, which is only 0.2% of India's total geographical area but is identified as one of the 34 global biodiversity hotspots (Myers et al., 2000). Khangchendzonga National Park is a UNESCO World Heritage site in the mixed natural/cultural category.

The local community includes Gurungs and Mangers-traditional shepherds, Bhutia-traditional traders and yak herders, Limboo-hunter-gatherers and shifting cultivators, the Chettris and Bahuns who were traditionally agro-pastoralists and Tibetan Dokpas-nomadic Yak herders (Tambe and Rawat, 2009a). Historically, only 10–15% of the study area's total households practiced pastoralism. The majority of families were involved in agriculture and cultivated cash crops, such as large cardamom, maize, and vegetables like potato and cauliflower. People also worked as a wage laborer in the agricultural fields of relatively wealthier families. At least one person from each household is also eligible to get work under the Mahatma Gandhi National Rural Employment Guarantee Act 2005 (MNREGA). The region, and especially Yuksam is also popular amongst the international trekking community and gained increasing attention in the last two decades, as the starting point of the Yuksam-Dzongri-Geochala trek to the base of Mount Khanchendzonga. With the influx of tourists, a few households in Yuksam village cluster also got involved in the hotel and restaurant business.

KNP has a wide range of ecosystem from sub-tropical to alpine with numerous lakes and peaks of religious importance to Sikkim's Buddhist and Hindu communities. The park harbors a unique assemblage of mammals which includes clouded leopard (*Neofelis nebulosa)*, Tibetan wolf (*Canis lupus chanco*), wild dog (*Cuon alpinus*), Asiatic black bear (*Ursus thibetanus*), Musk deer (*Moschus chrysogaster*), Himalayan marmot (*Marmota himalayana*), blue sheep (*Pseudois nayaur*), argali (*Ovis ammon hodgsoni*), ibex (*Capra sibirica*), and the charismatic snow leopard (*Panthera uncia*) (Sathyakumar et al., 2011). It is home to an extraordinary faunal diversity with 18 forest types (Champion and Seth, 1968), 1,580 species of vascular plants comprising 106 pteridophytes, 11 gymnosperms and 1,463 species of angiosperms (Maity and Maiti, 2007). Holding critical ecological, religious, and cultural importance, KNP has been designated a UNESCO World Heritage site.

MATERIALS AND METHODS

The primary data used in this study was collected during two phases, first during October–December 2017 and second between September and November 2019. During the pilot surveys conducted in April 2017, we identified four village clusters essential for examining the proposed questions in the landscape. Majority of the herders who used KNP for their livestock rearing were from these village clusters. Herders from these clusters' reared sheep, cattle, yak, dzo, and horses in the KNP and KBR area. According to the key informant interviews, ~103 herders used to herd their livestock in KNP. The majority of these (close to 70%) were from four village clusters selected for this study. We attempted to cover the maximum number of ex-herders during the field surveys and could conduct interviews with 50 ex-herders (40 semistructured interviews and 10 in depth interviews). Many of the elderly ex-herders had died of old age, and some had moved to the capital city Gangtok and other parts of Sikkim after selling their animals. We could not trace the herders who had moved out. The ethical approval for this research was received from the Research Studies Committee at the Ambedkar University Delhi and informed oral consent was gained from all the respondents.

We used mixed methods and conducted 48 semi-structured interviews, ten in-depth key informant interviews, and two focused group discussions. Among the 48 semi-structured interviews were forty ex-herders, three interviews with the forest officials, four interviews with members of local and regional conservation organizations- who had an essential role in implementing the ban, and one with a senior journalist who has been writing about the conservation issues in the region for more than two decades. Despite several attempts, we could not secure interviews with most of the forest officials involved in planning and implementing the grazing ban policy.

We prepared a list of ex-herders for each village cluster with the help of the elderly ex-herders of Yuksam village cluster first. We crosschecked the list in each village cluster and deployed the snowball sampling technique to maximize the number of interviewees. In-depth questions related to the historical pastoral system and changes in pastoralism were reserved for the elderly ex-herders only ($n = 10$), and the data collected was triangulated with the secondary data analysis. Semi-structured interviews were conducted with 48 respondents to understand the perceived social and ecological influence of the ecotourism and grazing ban in KNP. Respondents were asked about the social and environmental impacts of the grazing ban and ecotourism on the KNP and the local community.

Qualitative data from the interview transcripts and related set of notes were analyzed using the content analysis technique following "open coding process" where the data was assembled in blocks and patterns and examined concerning the context in the indexed text-based dataset. All the primary data was supplemented with the secondary data analysis of published and unpublished reports, research papers, newspaper articles and data from the livestock husbandry department. This helped in our understanding of the pastoral system's historical trends, significant events in the history of pastoralism, and how the state implemented conservation and tourism-related policies around KNP.

RESULTS

Historical Accounts of Pastoralism in Sikkim

Since Monarchy, pastoralists have had rights to graze in the forests of Sikkim, and in return provided a herding tax to the monarch of the kingdom. The Kazis who were landlords collected the herding tax annually (Lachungpa, 2012). Livestock herding has been a vital livelihood practice in the West Sikkim. Local communities, before the grazing ban, reared sheep, goat, cow, buffalos, and yak. Local herders used the temperate, sub-temperate and alpine pastures in and around KNP for the seasonal rotational grazing. The region has a diverse social composition of herders consisting of Bhutia, Lepcha, and Limboo community members with more recent immigration from Nepal, during the 1950s, who currently comprises more than 50% of the total population of Sikkim now (Duff, 2015). *Bhutia* were primarily yak herders but also engaged in agriculture and trade, they migrated from Eastern Tibet to Sikkim in the 14th century. *Limboo*, the traditional cattle herders and butchers also have originated from Tibet. Limboos and the Lepchas, who have been primarily the agriculturists, are one of Sikkim's earliest settlers (Duff, 2015). Immigrant population from Nepal includes members from the *Gurung*, *Mangar*, and *Chhetri* community who traditionally reared sheep and cattle.

The monarchy had a significant role in resource management by the herders in the past. In 1911, the tenth Chogyal of Sikkim, Sidkeong Tulku marked Sikkim's forests as reserves and community forests (Gupta, 1975; Lachungpa, 2012). Following the principles of sustainable management of natural resources, and prioritizing the villagers' needs for grazing land and firewood requirements, in 1911, patches of forests in the vicinity of the villages were notified as "forests reserved for the village" under categories of *khasmal* forests and *gaucharan* forests. The *gaucharans* were primarily the area designated for livestock grazing and meet their livestock requirements. The yaks, sheep and cattle grazed in these *gaucharans* during winter (Lachungpa, 2012).

Yak herding in west Sikkim was first introduced during the monarchy to worship Mount Khanchendzonga and celebrate the *Pang Lhabsol* festival for the prosperity and protection of the kingdom. There was only one yak herd that belonged to the King till the late 1950s. Yak rearing in West Sikkim was thus more of a cultural practice than an economic activity. Other livestock species, such as cattle, buffalo, dzo-hybrids of yak and cattle- have been introduced in the last 70 years (Tambe and Rawat, 2009a). Before that herders of west Sikkim reared only sheep and yak. Both sheep and yak herding followed a seasonal resource use. Herders used to keep the yak and sheep in the high-altitude alpine region of KNP in summers, In the peak winters, i.e., November to March, they were brought back to the temperate and sub-temperate pastures near the villages. There are also traces of fascinating historical instances of conflict over the pasture use between the pastoral communities mediated by the British during 1834–35 (Gupta, 1975). Pastures were also a source of medicinal plants and that were sold in the markets (Singh et al., 2002; Idrisi et al., 2010). The most important and lucrative income source, the caterpillar fungus, has medicinal value and is sold in the international markets at a very high price (Maity, 2013).

Demographic Changes, Tourism, and Livestock Compositions

Sikkim became the 22nd State of the Indian Union on 16th May 1975 after 300 years of being a monarchy Kingdom in Himalaya (Gupta, 1975). In the late 1980s, the Government of Sikkim relaxed restrictions on national and international tourists to raise state revenues through tourism. During the 1990s, the number of tourists increased exponentially (Rai and Sundriyal, 1997). The immigration of people from Nepal had steeply increased during the period of colonial influence. Post-merger with India, Sikkim experienced another wave of mass immigration from Nepal and immigrants began settling in Sikkim villages.

In west Sikkim, following better connectivity and linkages to the market, many yak and cattle herders from Nepal settled in the bordering villages of Nepal and Sikkim, which increased the livestock numbers many folds (Duff, 2015). Other than yak and sheep, herds of cattle became a common sight. With the increasing numbers of livestock and herders, livestock grazing, earlier restricted to *gaucharans* became comparatively intense and pervasive in the region.

Demographic changes and increased tourism at the regional level influenced pastoral practices and livestock numbers and composition in and around KNP. While the traditional pastoralism was restricted to yak and sheep herding (Tambe and Rawat, 2009a), immigration and tourism brought cattle, buffalo, horses, and the hybrid of cow and yak-locally known as *Udaag and Dzo*. Dzo was first introduced in KNP in 1971 when four dzos were bought from Nepal by villagers of Tshoka, a village settled inside present-day KNP by the former King of Sikkim, the *Chogyal*[1]. Several interviewees highlighted that the late Sir Tenzing Norgay, world-famous mountaineer, and member of the Himalayan Mountaineering Institute (HMI) provided a loan to buy and operate pack animals to carry rations and trekking gear from Yuksam Bazar to HMI base camp inside KNP. By 2000, Tshoka's four dzos had increased to 24 dzos, three horses, and 30 cows (personal conversation, ex-resident of Tshoka village and ex-dzo herder, October 2017).

Inside KNP the total number of dzo exceeded 100 by the year 2000 and primarily catered to tourism. Concurrently, there was a 10-fold increase in the number of yaks in the villages situated on the India-Nepal boundary. Yak numbers inside KNP, which were <100 before Sikkim's merger with India, reached above 850 by the year 2002 (**Figure 1**). These dzo, yak, and horses belonged to the villagers primarily from the study area's four village clusters. Dzo, horse and udang, which were not the traditional livestock species in the region, reached 785. Sheep, on the other hand, showed a decline of 87% between 1950 and 2004 (**Figure 2**).

Conservation Policies and Pastoral Transition in KNP

As mentioned earlier, tourism in and around KNP, started increasing in the late 1980s due to the relaxation in rules and regulations on domestic and foreign tourists (Karan, 1987, 1989) which were earlier restricted for security reasons. During the same period, following the state's conservation mission, the boundaries of KNP were extended from 850 to 1,789 sq. km. In the year 2000, Khangchendzonga Biosphere Reserve (KBR) was notified, resulting in the combined area of KNP and KBR reaching to 2,620 sq. km, one-fourth of the state's total area. A number of restrictions on community use of natural resources were implemented in the reserve and protected areas. In 1995 forest felling and export of timber in the protected area was restricted.

The grazing ban policy was formulated in 1998, and cattle grazing in the Reserve forests as restricted, followed by the Sikkim Forests Cattle Trespass Rule in the year 2002 (Government of Sikkim, 2006; Lachungpa, 2012). During the field surveys, the key respondents mentioned that the grazing ban policy was based on the assumption of overgrazing. Ecologists working in the area claimed that the herding practices in KNP were negatively influencing the vegetation and the wild herbivore population of the region (Tambe et al., 2006; Tambe and Rawat, 2009a). According to the key respondents ($n = 10$), no research was conducted prior to the grazing ban policy to assess or quantify the effects of grazing. Majority of the key respondents ($n = 9$) believed it was not the grazing by livestock, which was a conservation challenge, but a few influential herders engaged in the illegal timber and medicinal plant extractions.

Following the grazing ban's announcement, between 2002 and 2004, there was forceful removal of herders from the protected areas across Sikkim, except for North district. Based on the conversation with ex-herders and the key respondents, in our study area in West Sikkim, a total of 103 herders who had a little over 200-*goaths,* the temporary shelters for rearing livestock—were evicted during this period. The grazing ban resulted in the complete exclusion of locals and especially herders from KNP. The livestock composition that was slowly being influenced by tourism in the region had a significant shift after the grazing ban. Traditional livestock rearing got entirely wiped out from West Sikkim, especially in and around KNP.

In years between 2002 and 2004, while the Government of Sikkim restricted pastoralists' access to pastures, the state policies were encouraging dairy business by distributing non-native hybrid cattle. The indigenous cattle were being replaced with the new hybrid cattle in the study area with the State's Dairy Mission and the hybrid cattle distribution program. The state was promoting these new hybrid cow varieties to support the local economy with milk production. The market-oriented plans of the state were also detailed in an assessment report specifically noting "There was strong political will from the greenest Chief Minister Dr. Pawan Chamling to convince the herders to shift

[1]According to one of our respondents, late. Tsonam Ongye, Tenzing Norgay, the world-famous mountaineer had himself suggested his father to buy Dzo to carry ration, trekking gears and tools for the base camp inside KNP.

from herding large numbers of less productive cattle to limited numbers of productive cattle" (Tambe et al., 2005). Demand for dzo continued with increasing numbers of tourists on Yuksam-Dzongri trekking (Rai and Sundriyal, 1997). Yak rearing, a practice encouraged by the *Chogyal*-the monarch, to embrace the local cultural and religious importance in the past, was now seen as a backward way of living. Increasing tourism demanded pack animals and restrictions on pastoralists livelihood inside the park left most pastoralists of KNP with no other option but to quit pastoral practices. Some of the ex-herders and a few others started rearing pack animals since this was the only practice allowed for the locals in KNP. The long-term influence of tourism, the state's vision of KNP, and eventually the grazing ban transformed KNP from a pastoral cultural landscape to a tourist destination.

The state's participatory conservation and development attempts came *ex post facto* when herders had already been removed from the protected areas. Notifications for Eco-Development Committees were issued in 2002, and a network of committees was formed the same year. With a lack of human resource for patrolling the remote and rugged terrain, *Himal rakshak* program was launched (Singh, 2020). Ex-herders were designated honorary guardians of the mountains to help the forest department patrol the high-altitude rangelands and support the conservation initiatives in and around KNP. In the same year, the State Green Mission was announced to reinforce further Sikkim's already widespread recognition as being a green state (Lachungpa, 2012).

At present, there are 248 pack animals in the KNP region which belong to 47 households. These pack animals, primarily dzo and horses, are hired to trekking tours at \$6–7 per animal per day. Pack animals carry the trekkers' personal load, camping equipment, ration, and other useful things crucial for the 9–12 days of treks. There are two trekking seasons in KNP, between early March to mid-June in summers and between September to early December in winters. During these two time periods, the pack animals follow the trekking trails from Yuksam to Geochala and graze at typical camping and resting places for trekkers.

Perceived Social and Ecological Influences

Respondents mentioned a range of social and ecological influences of the exclusion model of pastoral evictions combined with eco-tourism in and around KNP. A total of 179 responses were recorded from 48 respondents, which included both positive and negative influence on the region's ecology and social components (**Table 1**). The grazing ban's two most critical impacts were the cultural loss (22.34% responses) and economic loss (18.43% responses) associated with the pastoral practices. The respondents mentioned that while the state evicted most herders from the park post the grazing ban, the most influential yak herders ($n = 3$) continued to stay inside the park and continued yak herding.

In more than 11% of responses, it was highlighted that the grazing ban had resulted in marginalization of the pastoralists and has favored the local and non-local elites. Out of the total ex-herders that we interviewed ($n = 50$), who lost their pastoral livelihoods for "saving" the floral and faunal diversity of KNP, only 13% ($n = 6$) were now involved in the livelihoods associated with tourism. They were all working for the lowest paying jobs, such as porters and the pack animal operators. Only the elite within the local community benefitted since they can afford to establish hotels and homestays that are now rented by the tourists for INR 500 to 4,000 per night (\$7–\$55 per night). The number of hotels increased from four in the year 1998 (Rai and Sundriyal, 1997) to more than 26 hotels and homestays and eight restaurants in the year 2018 in Yuksam. Multiple conversations with the local tour operators revealed that the ex-herders and local youth committee members worked at the lowest paying jobs *viz* porters and cooks. Non-local tour operators from other states like West Bengal and Bangalore made the greatest profits from tourism activities in KNP. These operators worked at the national level and collaborated with the local guides from parts of Darjeeling and Sikkim.

TABLE 1 | Locally perceived influence of grazing ban and tourism in KNP.

Influence of grazing ban and tourism promotion	Percentage of responses ($n = 179$)
Economic and livelihood loss	22.34
Loss of culture	18.43
Increased inequality and elite capture	11.17
Changes in agriculture (from traditional to cash crop varieties)	7.8
Negative influence on the ecology of summer pastures with pastoral removal and current pack animal rearing	6.7
Altered ecology of winter pastures due to plantation	6.7
Increased events of human-wildlife conflicts	9.1
Helped in reducing illegal medical plant extraction and wildlife poaching	9.1
Improved education among pastoralist families	2.2
Increased income from tourism and homestays	0.5

Total number of respondents = 48, total number of responses = 179.

Respondents also believed that banning of the traditional rotational herding had influenced the ecology of the winter pastures. The locally perceived impacts include a decreased abundance of preferred forage species, late flowering of some of the high-altitude species, and increased dominance of the less preferred pasture species. The ex-herders ($n = 6.7\%$ responses) mentioned that many species require grazing to ensure contiguity in flowering periodicity. These respondents also raised concerns with the current pack animal management. At present, the pack animals graze in a limited area for 2–3 months where yak and sheep grazed earlier. But unlike rotational grazing practiced previously, pack animals are left in one space during the non-tourist season resulting in high stocking density and pressures on rangelands.

The respondents mentioned that the afforestation done after pastoral removal is also problematic (6.7% responses). As soon as the pastoralists were intimated of their impending removal, the forest department started conducting plantation drives in the region. Around the study area, saplings are still planted every year and fenced. Plantation and fencing were done in the *gaucharans*

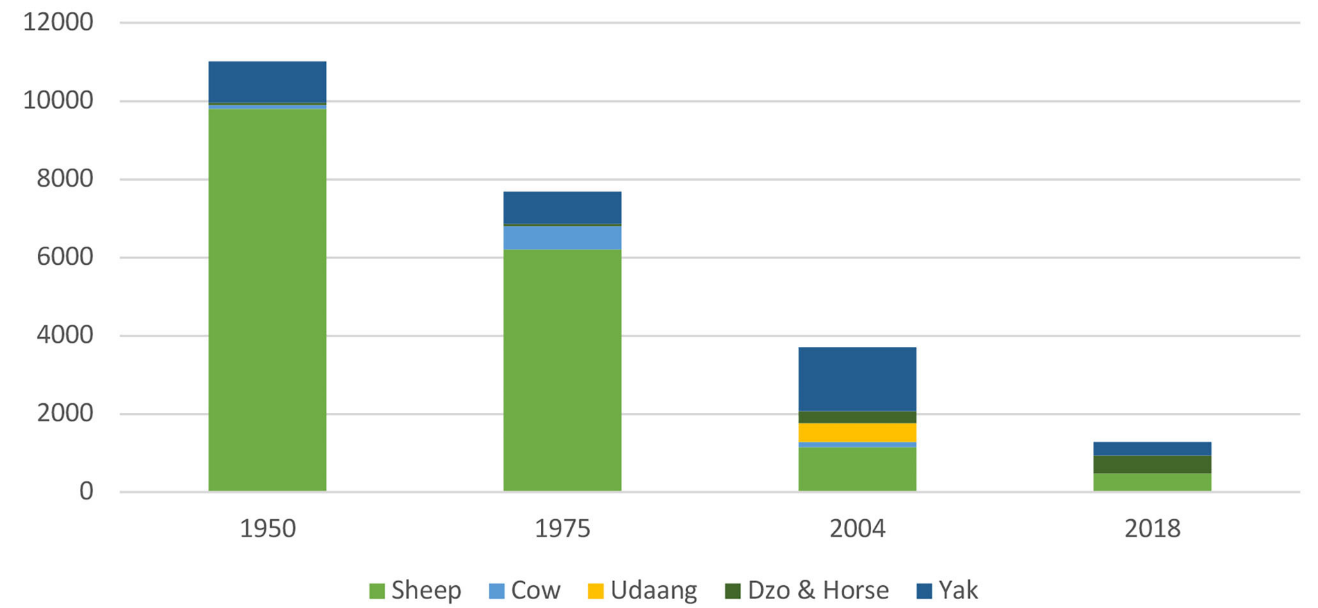

FIGURE 2 | Livestock numbers and composition change in KNP between the year 1950–2018, Source: (1950–2004, Tambe and Rawat, 2009b), 2018: Author's data.

and *khasmal,* which used to be livestock grazing grounds during winters. In the plantations, rather than focusing on the endemic species like *Quercus* spp, *Castanopsis* spp, forest department planted fruit-bearing trees like cherry, and species with economic values like *Magnolia* spp. and *Bambusa* spp., Bamboo being a fast-growing plant has helped increase the green cover, but not the local biodiversity. These plantation drives are still carried out by the forest department staff members every year.

One of the most critical issues highlighted by the respondents was an increase in the human-wildlife conflict (9.1% responses) events post-grazing ban. After removal from the park, most of the herders started cash crop plantations, which changed the traditional cropping pattern (as highlighted in 7.8% responses) to the cash crop plantation and increased events of crop damage by wild boar and bear and resulted in human-wildlife conflicts.

The positive influence of the grazing ban and tourism as perceived by the respondents included a reduction in illegal medicinal plant extraction and wildlife poaching (9.1% response), improved income with tourism and homestays and better education (2.2% responses) among the pastoralists families (0.5% responses).

DISCUSSION

Studies conducted across parts of Asia and Africa have highlighted that state-led conservation policies in the form of restrictions on pastoral mobilities, physical evictions and sedentarization tend to have a range of unfavorable influences on the social, cultural and ecological components of the pastoral systems and rangelands (Li et al., 2013; Conte and Tilt, 2014; Ichinkhorloo and Yeh, 2016). Conservation induced pastoral restrictions, coupled with tourism initiatives, result in the reinforcement of the local inequality by widening the economic gaps between small and big herders (Ichinkhorloo and Yeh, 2016), violate pastoral rights by unlawful encroachments of pastures (Mwaikusa, 1993), transition pastoral communities to agriculturalist in absence of access to pastures (Schmidt and Pearson, 2016), and cause loss of access and pastoral livelihoods through state violence and territorialization (Saberwal, 1996; Yeh, 2005; Gonin and Gautier, 2015; Korf et al., 2015; Caravani, 2019; Weldemichel, 2020).

Removal of pastoralists from the protected areas of Sikkim, followed by ecotourism, closely mirrors the conservation model in vogue in the states of Indian Himalaya. Many studies have highlighted the societal and ecological impacts of the conservation and tourism entanglements (Mwaikusa, 1993; Chhatre and Saberwal, 2006; Conte and Tilt, 2014; Das and Chatterjee, 2015; Ichinkhorloo and Yeh, 2016; Schmidt and Pearson, 2016; Brandt et al., 2019), but what is unique in the case of West Sikkim is the end of pastoralism in KNP. In some Himalayan states, pastoralists could sustain their livelihood by moving to new pastures or negotiating for rights and access with the state and forest department. With the limited summer pastures restricted to protected areas and the lack of the alternative regions for livestock grazing, the grazing ban caused the end of pastoralism in KNP, except for a few (<5) yaks herder who defied the ban and continued herding in KNP.

Regional entanglements of development, tourism and conservation policies reproduced the Khangchendzonga landscape from a pastoral cultural landscape to a tourism hot spot with exclusive access to the tourism and associated livestock species. Due to lack of any rehabilitation program, the conservation-tourism coupling resulted in a loss of access for most pastoralists inside KNP. Besides, while some ex-herders did adopt livelihoods associated with tourism, they have remained at the lower end of the tourism sector hierarchy getting low paying jobs like porters and cooks. These findings share similarities with studies conducted in pastoral landscapes in parts of Asia and Africa. In Inner Mongolia and Xinjiang, tourism activities in the pastoral landscapes resulted in a loss of access to traditional pastures. Pastoralists, who adopted tourism-related livelihoods remained on the lowest paying jobs (Lam and Paul, 2014). Similarly, in case of Kenya, the government implemented conservation and tourism policies to diversify livelihood incomes of Mara pastoralists resulted in restrictions on livestock mobility and reduced access to good quality pastures (Bedelian and Ogutu, 2017).

In the study area, within the local community, local elites have managed to reap most of the benefits with the conservation and tourism coupling, a phenomenon also seen in the state-led conservation-development model in the similar socio-political contexts of Tanzania (Mccabe et al., 1992; Weldemichel, 2020), Uganda (Cavanagh and Benjaminsen, 2014), and Columbia (Ojeda, 2012). Negative social influences, such as social disparity and the emergence of conflict between the villages in West Sikkim share similarity with other geographies with the policy implementation of pastoral bans. For example, in Mongolia, failing to account for a pastoralist community's heterogeneity, one such approach resulted in widening the gap between the small subsistence-based herders and powerful big herders by giving more power and access to the later (Ichinkhorloo and Yeh, 2016). In China, a grazing ban and sedentarization policy resulted in deterioration of clan social bonds crucial for the community resource use, subsistence and dealing with the climatic and social variabilities (Conte and Tilt, 2014).

Respondents mentioned that the removal of pastoralists and the current pack animal rearing practices in KNP, might have adverse effects on the area's ecology. Degradation of pastures by the changes post a grazing ban and the new private grazing approach has also been seen in Inner Mongolia (Conte and Tilt, 2014). A recent study conducted across 15 biodiversity hotspots in four Himalayan countries Nepal, Bhutan, China and India found that relationship between the conservation and ecotourism is highly context-specific and that in India forest loss in the ecotourism sites was higher than the control site without ecotourism (Brandt et al., 2019). Also, the grazing ban and removal of pastoralists from the park has led to new conservation challenges in increasing human-wildlife conflict incidents. The transition from a traditional livestock herding to pack animal rearing and removing pastoralists from KNP has neither benefitted the ecology nor society.

One of the significant drawbacks of the grazing ban and ecotourism in KNP is lack of local participation at the planning stage. Participation was only sought in the form of *formation* of the Eco-development Committee (EDC), Joint Forest Management Committees (JFMC) and the *Himal Rakshak* Programme (Government of Sikkim, 2006). But the members of all three programs were supposed to simply follow the state instructions of afforestation for the first two and monitor the rangelands for the third. The local community members of these committees were not involved in identifying the problems or suggesting potential solutions to issues, such as the increasing tourist footprint in the protected areas. Better local participation could have elevated local actors in the tourism sector at a higher level and not limited to potters and guides' jobs. The absence of local consultations paved the way for external tourist operators to establish themselves in and around KNP and further marginalized the local community.

The grazing ban policy was forced on the pastoralist of KNP by highlighting the negative impacts of grazing during the "sensitization" meeting conducted with the herders. The pastoralist's views on the role of grazing in influencing rangeland biodiversity were neither sought nor understood. Pastoralists, the prime users of rangelands were not consulted regarding potential alternatives that could have harmonized pastoral communities' needs and conservation concerns. The knowledge of ex-herders, who were pushed out of KNP and had lost their livelihoods, was later feted as "mountain guardians" to help conserve and manage the remote regions of KNP. Instead of taking an exclusionary approach, engaging the ex-herders and the local village community members in conservation planning could have resulted in better outcomes for resource management, livelihoods and conservation. In hindsight, limiting the livestock numbers based on the rangeland carrying capacity and ensuring equity amongst herders rather than ending the cultural practice of pastoralism could have been a viable solution.

The transition from self-sufficient herding practice to the market-driven economy has made the local communities highly vulnerable to external risks and shocks. Political unrest in the neighboring State of West Bengal and constant landslides in the region have been chief issues that influenced the new tourism-based economy of West Sikkim. The recent emergence of Covid-19 and the resulting closure of tourism in Sikkim highlighted how state induced pastoral transition has magnified the local communities' vulnerability to external factors like never before.

CONCLUSION

In this article, focusing on pastoral practices in KNP, we show how the conservation-pastoral eviction- tourism coupling resulted in the transition of traditional herding to pack animal economy and have transitioned KNP from a pastoral cultural landscape to an exclusive tourist spot. The livestock composition, which was slowly being influenced by the demographic changes and tourism influence, became drastically altered post the grazing ban causing and end to the traditional pastoralism. The locally perceived adverse effects of the grazing ban and current tourism practices include wide-ranging social and ecological issues and the emergence of new conservation challenges in increased human-wildlife conflict incidents. Building on the case study of KNP, we suggest that instead of curtailing local participation which is one of the most significant critiques of environmental policies globally, the state should fully and meaningfully involve pastoralists, the primary stakeholders of high altitude rangelands in designing and implementing conservation plans. Since most of the high altitude areas in Himalaya share International borders, the conservation and development planning could also benefit from trans-boundary level planning and cooperation.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Research Advisory Committee, School of Human Ecology, Ambedkar University Delhi. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

RS conceived the study, conducted fieldwork, and wrote the manuscript. RKS provided intellectual inputs in study design, manuscript writing, and revisions. TUB and KB contributed to study design and data collections. SB provided overall guidance in study design, data collection, and analysis. All the authors edited and approved the final manuscript.

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frontiers in Sustainable Food Systems

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Designing Diverse Agricultural Pastures for Improving Ruminant Production Systems

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Pasture-based production systems represent a significant sustainable supplier of animal source foods worldwide. For such systems, mounting evidence highlights the importance of plant diversity on the proper functioning of soils, plants and animals. A diversity of forages and biochemicals –primary and secondary compounds- at appropriate doses and sequences of ingestion, may lead to benefits to the animal and their environment that are greater than grazing monocultures and the isolated effects of single chemicals. Here we review the importance of plant and phytochemical diversity on animal nutrition, welfare, health, and environmental impact while exploring some novel ideas about pasture design and management based on the biochemical complexity of traditional and non-traditional forage sources. Such effort will require an integration and synthesis on the morphology, ecophysiology, and biochemistry of traditional and non-traditional forage species, as well as on the foraging behavior of livestock grazing diverse pasturelands. Thus, the challenge ahead entails selecting the "right" species combination, spatial aggregation, distribution and management of the forage resource such that productivity and stability of plant communities and ecological services provided by grazing are enhanced. We conclude that there is strong experimental support for replacing simple traditional agricultural pastures of reduced phytochemical diversity with multiple arrays of complementary forage species that enable ruminants to select a diet in benefit of their nutrition, health and welfare, whilst reducing the negative environmental impacts caused by livestock production systems.

Keywords: diverse pastures, phytochemical diversity, ruminants, environmental impacts, animal nutrition, animal health, animal welfare, animal production

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INTRODUCTION

Numerous current studies highlight the importance of plant diversity for the proper functioning of soils, plants and herbivores (Eisenhauer et al., 2018; Hautier et al., 2018; Schaub et al., 2020). This is because plant diversity affects soil physical, chemical, and biological attributes, both indirectly through the promotion of biomass production, and directly through plant species, to soil attributes and functioning (Coleman et al., 2017). Plants feed and grow soil biota through their litter and root-derived organic inputs (i.e., root exudates, root necromass), which are increased by plant diversity (Zak et al., 2003). In addition, plant species differ in belowground structure and function, which influence soil biota and directly relate to soil functioning (McNally et al., 2015; Eisenhauer et al., 2017). Recent results have demonstrated the importance of soil biodiversity for soil functionality at the local level and across biomes (Delgado-Baquerizo et al., 2020).

With regards to primary productivity, many studies, and meta-analyses have shown that plant diversity increases the productivity and stability of plant communities (e.g., Hector et al., 1999; Tilman et al., 2001; Isbell et al., 2009, 2015, 2017; Polley et al., 2013; Prieto et al., 2015). The three primary mechanisms that have been proposed to explain the positive relationship between plant diversity and plant productivity are niche differentiation, positive interactions and selection effects (Hector et al., 2002). Niche differentiation arises due to species differences in morphological and physiological characteristics, which allow differential use of resources in space and time, thus increasing primary productivity when grown in mixtures. Positive interactions result from facilitation between species [e.g., associative nitrogen fixation from legumes to grasses (Kakraliya et al., 2018)], whereas selection effects result from an increased probability of the presence of species that perform the best in a certain growing environment (Valencia et al., 2018). Plant communities composed of different functional groups of species are also expected to exhibit greater temporal stability in yield, because they are more resistant or resilient to environmental or biological disturbances due to differences in tolerance among species (Cottingham et al., 2001; Polley et al., 2013). Note that plant communities composed of species functional groups with different responses to changes in environmental conditions become critical in the face of future climate change. Finally, plant diversity is strongly correlated with phytochemical diversity at the community level (Moore et al., 2014; Marzetz et al., 2017), which is a biological need for the ruminant animal's optimal expression of its potential functioning (Provenza et al., 2007).

Plant diversity, and the inherent phytochemical diversity in plant communities, are biologically important to the ruminant animal for several reasons. First, ruminants are generalist herbivores and they evolved experiencing a multidimensionality of orosensorial and post-ingestive stimuli that contribute to improved fitness (e.g., Rapport, 1980; Provenza et al., 2007; Beck and Gregorini, 2020). Dietary mixing is thought to benefit herbivores by allowing either a more balanced intake of nutrients (Westoby, 1978; Rapport, 1980; Provenza et al., 2003) or a diluted ingestion of toxins (Freeland and Janzen, 1974; Marsh et al., 2006). A corollary of dietary mixing theory is that it allows generalist herbivores to reach similar fitness in habitats with different forage and chemical compositions (Franzke et al., 2010). For instance, metabolic disorders caused by excessive nutrient intake from a single forage could be diluted by ingesting alternative sources that differ in nutrient concentration (Rutter, 2006). Phytochemical diversity may also help counteract toxicity caused by single plant secondary metabolites (PSMs), because nutrients attenuate the negative post-ingestive effects of certain toxins through an enhancement in detoxification and elimination pathways (Illius and Jessop, 1995), and because some PSMs form stable complexes with other PSMs in the gastrointestinal tract that attenuate toxicity (Villalba and Provenza, 2005; Copani et al., 2013). In addition, ingestion of diverse PSMs, at appropriate doses, could provide medicinal benefits (Cozier et al., 2006), improve product quality (Priolo and Vasta, 2007; Vasta et al., 2019), and reduce the negative environmental impacts from ruminants' (e.g., enteric methane and nitrous oxide emissions, and nitrate leaching; Mueller-Harvey et al., 2019; Clemensen et al., 2020; Lagrange et al., 2020). Finally, individuals differ in their need for nutrients and tolerance to toxins due to inherent morphological and physiological differences (Provenza et al., 2003). Therefore, a diversity of forage species allows for the expression of such individual variability and a better fulfillment of individual needs than a uniform diet designed to satisfy requirements for the average animal within a group.

Even though there is mounting experimental evidence on the importance of plant diversity for soil, plant and ruminant animal's functioning, and thus on farmer profitability (Schaub et al., 2020), current agricultural pasture systems are usually composed of either one or a few "conventional" or widely known plant species. There is a need for designing diverse agricultural pasture systems, to replace traditional ones of limited diversity. Nevertheless, devising diverse pasture-based grazing systems for improving ruminant production and welfare, while reducing environmental impacts, entails a big challenge. It requires an extensive set of work of analysis, integration and synthesis of knowledge on the morphology, physiology and biochemistry at the plant species and biochemical level, and on the interactions among plant species/genotypes/chemicals under grazing conditions. From this complexity, it may be possible to create pasture mixtures that on the one hand enhance primary productivity through complementary and positive interactions between species, and on the other, enhance animal health, welfare and the efficiency of nutrient use by ruminants.

This review is limited to a consideration on the importance of plant diversity for ruminants to perform at their potential, and some ideas on designing diverse pasturelands and chemical landscapes (i.e., chemoscapes). Our aim was to highlight the key role of forage diversity on ruminant production systems, given that there is emerging experimental evidence on the benefits of chemically and taxonomically diverse plant communities on animal fitness. Then, we engage in some basics of pasture design, such as selection of species composition, spatial arrangement and grazing management of forage mixtures. By this means, we expect to stimulate novel fundamental research and applied approaches aimed at the design of diverse pasturelands that enrich the ruminant's environment and enhance the system's efficiency while remaining productive for multiple years.

AN EXPLANATION FOR DIVERSE DIETS IN RUMINANTS

Dietary diversity is ubiquitous among mammalian herbivores. When allowed to select among alternative foods of different types and concentration of nutrients and PSMs, ruminant animals learn to select varied diets that meet their nutritional requirements and circumvent toxicity and nutritional disorders

(Provenza, 1995; Villalba et al., 2002, 2004). Nutrient constraints and detoxification limitations have been proposed as alternative biological bases of varied diets. The "nutrient constraints" or "nutrient complementation" hypothesis argues that no one plant species can provide all nutrients in the proportion needed by herbivores and thus dietary mixing allows for a more balanced nutrient intake (Westoby, 1974, 1978; Rapport, 1980). The "detoxification limitation hypothesis" argues that the detoxification systems of animals are incapable of metabolizing high levels of PSMs present in a single plant species, and thus, PSMs ingested as a mixture are less toxic because they are less concentrated and potentially detoxified by different pathways (Freeland and Janzen, 1974). These hypotheses are not mutually exclusive, and both assume an underlying physiological and behavioral mechanism.

Transient food aversion has also been proposed as a non-mutually exclusive alternative to nutrient balancing and toxin dilution for explaining partial preference and diverse diets in ruminant animals (Provenza, 1996). The underlying mechanism of food aversion is the association between sensorial receptors (that respond to a food's taste, odor, texture, visual aspect) and visceral receptors (that respond to chemical and physical stimuli), which enable herbivores to learn through post-ingestive consequences (Provenza, 1995). Temporary food aversions develop when the same food is consumed too frequently or in excess, when the food is nutritionally imbalanced, restricted in nutrient content or when it contains toxins (Provenza, 1996). Through this mechanism, animals attempt to fulfill their metabolic requirements and achieve homeostasis (Villalba and Provenza, 2009). Note that, animals can develop temporary aversions even for nutritionally balanced diets, since animals satiate when the same food is eaten repeatedly or in excess (Provenza, 1996). It has been argued that hedonic and motivational incentives associated with foods, through experiences and expectations of rewards, are also determinants of feeding behavior (Ginane et al., 2015).

In summary, the transient food aversion hypothesis suggests that dietary diversity is based on the nutritional and toxicological disorders experienced by ruminants consuming nutritional unbalanced and/or potentially toxic feeds. Such disorders (e.g., acidosis, hyperammonemia, bloat, toxicity) commonly occur when herbivores are faced to single feeds. If alternative complementary foods are available, animals could circumvent this constrain through their diet selection. For instance, lambs increase their preference for a chemical buffer (bentonite; Villalba et al., 2006, sodium bicarbonate; Phy and Provenza, 1998), and dairy cows increase their intake of larger feed particles that stimulate saliva production (Kmicikewycz and Heinrichs, 2015) when experiencing ruminal acidosis. High intakes of readily degradable sources of nitrogen lead to increments in the concentration of ammonia in the peripheral circulation once the liver detoxification threshold is surpassed (Lobley and Milano, 1997). This increase causes reductions in food intake, mediated through aversive post-ingestive feedback, which occurs very quickly within a meal (Villalba and Provenza, 1997). Sheep fed a basal diet high in rumen-degradable protein and allowed to ingest a feed with condensed tannins (PSMs that bind to proteins and reduce their ruminal degradability) showed reduced rumen ammonia nitrogen and blood urea nitrogen, and a tendency to develop a preference for and intake of the tannin-containing feed (Fernández et al., 2012).

Pasture bloat occurs in fresh, high-protein forages, with high rate of particle breakdown that results in a rapid release of plant soluble proteins and disruption of chloroplasts, providing large quantities of gas and bacterial slime, which create a stable foam that prevents the animal eructation of fermentation gases (CO_2 and CH_4), and thus promote rumen distension (Majak et al., 2003). Sheep learn to avoid foods that cause rumen distension and to prefer foods that attenuate this effect (Villalba et al., 2009).

The aforementioned theories of partial preference focus on just one aspect of diet like presence of plant toxins, flavors or nutrients. A multifaceted theory that considers processes beyond feed properties like motivation to eat (e.g., Ginane et al., 2015) and interactions with other factors such as the animal's past experiences (e.g., Provenza, 1995), sequence of feed ingestion (e.g., Yearsley et al., 2006) and energetic costs of food acquisition and processing (e.g., Hobbs et al., 2003) is still lacking, although the transient food aversion hypothesis is a first approach into fulfilling this need.

DIVERSE DIETS: NUTRIENTS, PLANT SECONDARY METABOLITES, AND FLAVORS

Ruminants grazing diverse chemoscapes are faced with the complex task of building a diet with appropriate proportions and concentrations of nutrients that satisfy their individual needs, while balancing the ingestion of potentially toxic (but also medicinal) PSMs (Provenza, 1995; Villalba et al., 2017). In the process, animals are exposed to a diverse array of flavors that influence their grazing behavior (Villalba et al., 2011). This section reviews the influence of nutrients, PSMs and flavors during grazing on some key aspects of animal nutrition, health, welfare, and environmental impact.

Diverse Diets: Nutrient Intake

A diversity of forages and biochemicals available in pasturelands may enhance the nutritional benefits that forages offer to ruminants because complementary relationships among multiple food resources in nature improves animal fitness (Tilman, 1982). This is because diverse diets offer ruminants a variety of biochemicals (nutrients and PSMs) which allow for associative effects and synergies with the potential to enhance the efficiency of nutrient utilization relative to single forage species in monocultures (Provenza et al., 2003; Waghorn and McNabb, 2003). Biodiversity in pasturelands may lead to positive associative effects among forages, which improve the nutrition (i.e., nitrogen retention, diet digestibility) and welfare of livestock (i.e., reductions in stress caused by single forages with unbalanced nutrient profiles and monotonous flavors).

Ruminants mix forage alternatives that lead to a balanced diet at greater levels of intake than for single species (Askar et al., 2006; Villalba et al., 2015). For instance, sheep and goats eating mixed diets in rangeland display daily dry matter intakes two or more times greater than reference intake values obtained with animals fed single forages of similar nutritive value (Agreil and Meuret, 2004; Meuret and Provenza, 2015). The consumption of different legumes with contrasting chemical composition (i.e., different content of non-fiber carbohydrates, fiber and proteins) and presence of PSMs leads to associative effects, like rumen protein degradability lower than the average of the individual forages. This reduces ammonia formation (and thus its toxic effects and nitrogen loses to the environment) while increasing the amount of dietary protein reaching the small intestine (Mueller-Harvey, 2006; Waghorn, 2008). This is supported by *in vitro* studies for a mixture of sainfoin (*Onobrichis viciifolia*) and cocksfoot (*Dactylis glomerata*) (Niderkorn et al., 2012) and by *in vivo* studies with beef cows grazing combinations of sainfoin, alfalfa (*Medicago sativa*) and birdsfoot trefoil (*Lotus corniculatus*) (Lagrange et al., 2020). Moreover, since individuals differ morphologically and physiologically, the possibility of free choice among food alternatives allows for the expression of individual nutritional needs (Provenza et al., 2007; Baraza et al., 2009).

Cattle fed the ingredients of a total mixed ration in a free-choice test were able to select a diet adequate to meet their individual needs, without compromising gain (kg/day) and food conversion efficiency relative to a mixed ration that prevented animals from selecting individual ingredients (Atwood et al., 2001; Moya et al., 2011). Moreover, individual animals varied considerably in their preferred ratio of protein to energy, which resulted in lower food cost/day and cost/kg gain compared to animals fed the total-mixed ration (Atwood et al., 2001). In another study, sheep offered a free choice of three legume species, differing in nutrient and PSMs content, showed enhanced intake and diet digestibility relative to feeding single species (Lagrange and Villalba, 2019). Goats fed a free choice of five shrub species selected a mixed diet of greater digestibility than controls fed the single shrub species (Egea et al., 2016).

Diverse Diets: Environmental Impact

The challenge ahead entails creating diverse pastures that enhance phytochemical richness and enable animals to practice selectivity, whilst also having positive effects on the environment. Forage combinations with a diversity of biochemical compositions may contribute to reductions in carbon and nitrogen footprints by ruminant animals, a positive attribute that adds value to livestock products beyond their nutritional quality (Rochfort et al., 2008; Patra and Saxena, 2010). It is recognized that a negative byproduct of ruminant production systems entails negative environmental impact (de Vries and de Boer, 2010; de Vries et al., 2015). The largest contributing source of greenhouse gas (GHG) emissions from beef cattle production is enteric methane (CH_4), accounting for 56% (Rotz et al., 2019) to 63% (Beauchemin et al., 2010) of all GHG from beef industry and 39% of all GHG emissions from the livestock sector. Methane is a byproduct of the microbial fermentation of feeds in the rumen, which represents an energy loss to the animal that ranges between 2 and 12% of the gross energy consumed with the diet (Johnson and Johnson, 1995). Forages with high concentration of non-fibrous carbohydrates, that are readily fermented in the rumen (i.e., soluble carbohydrates plus pectin) and low proportion of structural carbohydrates (cellulose and hemicellulose), enhance the efficiency of nutrient use by cattle, yielding animal weight gains that are comparable to feeding high-grain rations (Chail et al., 2017; MacAdam, 2019). This chemical profile increases the proportion of potentially propionate-forming bacteria and decreases hydrogen production, which results in decreased CH_4 emissions relative to forages with lower content of non-fibrous carbohydrates (Sun et al., 2015; Stewart et al., 2019). *In vitro* rumen fermentation of perennial ryegrass forages differing in the concentration of water-soluble carbohydrates showed lower acetate:propionate ratio and CH_4 concentration in high than in low sugar ryegrass pastures (Rivero et al., 2020). Similarly, lambs fed fresh winter forage rape (*Brassica napus*) showed reduced CH_4 yields compared with lambs fed ryegrass, a response which was attributed to higher concentration of non-structural carbohydrates and lower ruminal pH in the former than in the latter forage species (Sun et al., 2012, 2015, 2016).

Incorporation of species rich in bioactive PSMs in diverse pastures also reduces CH_4 production in the rumen. For instance, legume species containing phenolic compounds (condensed tannins) like sainfoin have been shown to reduce methane emissions (Wang et al., 2015). A recent study showed lower numerical values of enteric methane emissions by heifers grazing combinations of legumes (alfalfa, birdsfoot trefoil, sainfoin) relative to controls grazing monocultures of the same species. Heifers offered the combinations showed the greatest body weight gains, implying reductions in the number of days to slaughter, which reduces methane emissions during the finishing process (Lagrange et al., 2020). Other legume species like *Macrotyloma axillare* also showed antimethanogenic potential, associated with a decrease in the relative abundance of methanogenic archaea and protozoa (Lima et al., 2018, 2020). Essential oils, of which terpenes are major compounds, have been demonstrated to reduce methane production during *in vitro* and *in vivo* studies (Cobellis et al., 2016).

Greenhouse gas emissions from livestock production systems also involve the production of the potent GHG nitrous oxide (N_2O) (Rotz et al., 2019). High levels of ammonia in urine "hot spots" are sources of this gas produced during microbial nitrification and denitrification processes (Oenema et al., 2005; Huang et al., 2015). Strategies to reduce problems with excess of nitrogen, while maintaining high levels of animal productivity, entails the provision of high sugar and bioactive-containing forages that increase nitrogen retention and/or reduce the proportion of urinary nitrogen losses. For instance, nitrogen use efficiency is higher in high than in low sugar ryegrass pastures (Rivero et al., 2020). Polyphenols, like condensed tannins in sainfoin or birdsfoot trefoil bind to proteins protecting their degradation in the rumen (Scharenberg et al., 2007; Theodoridou et al., 2010, 2012), which alters the fate of the excreted nitrogen to greater fecal to urinary ratios (Mueller-Harvey, 2006). A shift in the route of nitrogen excretion from urine to feces means more stable nitrogen fractions in manure since nitrogen is mainly bound to organic compounds like neutral detergent and acid detergent insoluble nitrogen, which lessens the rate of nitrogen losses to the environment (Whitehead, 2000; Grosse Brinkhaus et al., 2016; Stewart et al., 2019). A diversity in the chemical structures of condensed tannins in sainfoin and birdsfoot trefoil (McAllister et al., 2005) may influence their capacities to bind proteins and microbial enzymes in the rumen (Mueller-Harvey et al., 2019), which could promote positive associative effects that attenuate protein degradability in the rumen, and thus the fate of nitrogen excretion. In support of this, heifers grazing a choice between strips of sainfoin and birdsfoot trefoil showed declines in urinary nitrogen and blood urea nitrogen relative to animals grazing an alfalfa monoculture (Lagrange et al., 2020). Moreover, this decline was even greater than reductions observed for the single tanniferous species grazed individually. This novel finding suggests a positive associative effect between condensed tannins on the reduction of ruminal protein degradation, attributed to the different chemical structure of condensed tannins in different legumes. Condensed tannins in birdsfoot trefoil have average molecular weight of 4,400 Da (McAllister et al., 2005), with a degree of polymerization in the range of 6 to 14 of predominantly procyanidin type subunits of oligomers and polymers (Jonker and Yu, 2017), while sainfoin's condensed tannins are basically constituted by prodelphinidin monomers of a mean molecular weight of 5,100 Da (McAllister et al., 2005), with polymer sizes that vary between 4 and 12 subunits (Jonker and Yu, 2017).

Another problem with excesses of urinary nitrogen deposited in beef production systems entails the eutrophication of watersheds by nitrates, produced by ammonia oxidation and then leached into ground water, streams and lakes (Whitehead, 2000). Based on experimental results involving diverse pastures, in combination with a whole-farm model, significant reductions in nitrogen leaching were predicted for a well-drained soil in the Waikato region of New Zealand when replacing traditional simple forage mixtures by complex forage mixtures in dairy farm systems (Romera et al., 2017). An integrated modeling assessment of intensive sheep and beef production systems for the Cantebury region of New Zealand also predicted reductions in nitrogen leaching by using complex forage mixtures (Vogeler et al., 2017). For instance, the inclusion of forbs in can reduce nitrogen leaching (Totty et al., 2013; Bryant et al., 2018). The reduction in nitrogen leaching is strongly associated with declines in urinary nitrogen concentration, which may reflect either a better nutritionally balanced diet or PSMs-protein binding that decreases the amount of rumen degradable protein (Waghorn, 2008; Mueller-Harvey et al., 2019) in complex forage mixtures. Furthermore, reduced urinary nitrogen concentration in cows that graze diverse pastures can lead to significantly decreased nitrous oxide emissions during the denitrification process (Di and Cameron, 2016).

Diverse Diets: Plant Secondary Metabolite Intake and Toxic Effects

Ruminants grazing diverse landscapes typically encounter plants that, in addition to nutrients, contain potentially toxic PSMs. Mammalian herbivores can ingest toxins up to a threshold level determined by their potential detoxification capacity (Freeland and Janzen, 1974; Dearing et al., 2000, 2005). The accomplishment of this potential is dependent upon nutrient availability, given that nutrients (carbohydrates, protein) are needed to fuel detoxification mechanisms (Illius and Jessop, 1995; Villalba and Provenza, 2005). Moreover, because different toxins may be metabolized through distinctive detoxification mechanisms, food intake is less compromised if a diversity of PSMs is consumed such that no single detoxification pathway is saturated in the process (Freeland and Janzen, 1974). For instance, lambs consume greater amounts of dry matter when they have available a choice among feeds containing different types of PSMs that are metabolized through different detoxification pathways (oxalates, condensed tannins, terpenes) than when only one feed with one PSM is available (Villalba et al., 2004). Likewise, PSMs can bind to each other forming stable molecular bonds in the gastrointestinal tract (e.g., alkaloid-condensed tannins or alkaloid-saponins) that are not absorbed and then excreted through feces, which neutralize their negative post-ingestive effects. Sheep fed foods with different alkaloids and either condensed tannins or saponins, ate more food than when offered only the foods with alkaloids (Lyman et al., 2008). Similarly, when cattle and sheep grazed first a forage high in tannins or saponins, they subsequently increased their grazing time on alkaloid-containing forages (Lyman et al., 2011; Owens et al., 2012). Complexation of condensed tannins with alkaloids was confirmed during *in vitro* studies (Villalba et al., 2016; Clemensen et al., 2018).

In Mediterranean ecosystems, sheep and goats increase total shrub intake when tanniferous shrubs were fed in combination with a shrub high in saponins, suggesting complementarity between tannin and saponins (Rogosic et al., 2006, 2007). It has also been shown that sheep consume more food with either condensed tannins or terpenes when the basal diet was of high- rather than low-nutritional quality, highlighting the importance of nutrients at enhancing the animals' detoxification and elimination capacities (Baraza et al., 2005).

Diverse Diets: Plant Secondary Metabolite Intake and Medicinal Effects

In present intensive animal production systems, feeding is almost exclusively based on plant primary metabolites (mainly carbohydrates and proteins). Improved forage species and rations are low in concentration and profiles of PSMs given their potential toxic effects (see previous section). However, PSMs at the appropriate dose could provide medicinal benefits (e.g., Moreno et al., 2010). In addition, there is evidence that herbivores learn about these benefits and potentially self-medicate (Engel, 2003; Hutchings et al., 2003). For instance, it has been shown that sheep can form multiple malaise-medicine associations and prefer specific medicines based on different negative physiological states like acidosis, tannin or oxalate toxicosis (Villalba et al., 2006).

Parasitic infections represent one of the main vectors that challenge ruminant health (Hoste et al., 2006, 2015), which force trade-offs between nutrition and parasitism in foraging decisions (Hutchings et al., 2000). In order to counteract the negative effects of parasitism herbivores have also evolved behavioral mechanisms to self-select medicinal foods at effective doses of PSMs (e.g., alkaloids, terpenes, phenols) that minimize toxicity (Glasser et al., 2009; Amit et al., 2013; Villalba et al., 2017). Such mechanism involves the association of a food's flavor with its post-ingestive medicinal effects (i.e., prophylactic self-medication; Juhnke et al., 2012), or the chronic consumption of small daily doses of medicinal PSMs with the animals' diet (i.e., a preventive or prophylactic "feed forward" mechanism; Glasser et al., 2009; Villalba et al., 2014).

Following the same logic described for nutrients, a diversity of medicinal PSMs from an array of varied forages with different mechanisms of antiparasitic action, may increase their effectiveness relative to single PSMs (Hoste et al., 2006). Moreover, since large quantities of PSMs are required to achieve meaningful antiparasitic doses in ruminants (Waghorn and McNabb, 2003), a diverse diet with multiple PSMs may allow animals to harvest the appropriate amounts and ratios of nutrients while consuming diverse antiparasitic PSMs with fewer single harmful side effects to the animal. Thus, complementarities among multiple bioactive molecules have the potential to enhance medicinal effects over single chemicals (Spelman et al., 2006). For instance, minor chemical compounds in plants may act as synergistic metabolites, producing greater overall efficacy than individual components (Hummelbrunner and Isman, 2001). Six chemical compounds from the medicinal plant *Petiveria alliacea* did not show acaricide activity against the common cattle tick (*Rhipicephalus microplusticks*) when tested individually *in vitro*. However, when the compounds were combined, some of the mixtures exhibited a synergistic increase in acaricidal activity, promoting high mortality rates (Arceo-Medina et al., 2016). Such complementarities are not always observed in livestock production systems. For instance, sheep infected with the gastrointestinal nematode *Haemonchus contortus* and offered a choice between feeds containing condensed tannins or saponins (both antiparasitic PSMs), displayed greater levels of infection than control sheep offered either tannins or saponins in single rations (Copani et al., 2013). As described above, tannins and saponins cross-react and bind in the gastrointestinal tract (Freeland et al., 1985), forming stable complexes that reduce the bioactivity of the single compounds. Thus, the nature of the relationship among PSMs needs to be considered on a case-by-case basis, in order to gain reliable information on whether the combination of compounds in a diverse diet yields synergistic, antagonistic or independent medicinal effects.

Diverse Diets: Flavor Variation and Animal Welfare

Large ruminants are generalist herbivores and they evolved selecting a diverse diet with different orosensorial experiences (Provenza et al., 2007; Villalba et al., 2015). It has also been argued that dietary diversity reduces oxidative and physiological stresses and improves the nutritional status and welfare of animals (Beck and Gregorini, 2020). Forage diversity provides animals with varied sensorial and post-ingestive experiences that increase the motivation to eat (Meuret and Bruchou, 1994; Villalba et al., 2010). Sheep fed the same ration but in a choice of different flavors consumed more total dry matter and tended to gain more weight than sheep exposed to the same ration but containing single flavors (Distel et al., 2007; Villalba et al., 2011). As for toxins or nutrients (see section Diverse Diets: Plant Secondary Metabolite Intake and Toxic Effects), herbivores grazing monocultures of single species or monotonous rations satiate on the orosensorial characteristics of single feeds (i.e., sensory-specific satiety) due to transient food aversions caused by flavors ingested too frequently or in excess, and satiety can be stressful (Provenza, 1996). However, if diverse options are available, animals continue responding to other orosensorial dimensions. This response has been attributed in part to the sensory properties of food, because an animal that stops eating one flavored food will often consume another food or the same food presented in a different flavor (Provenza, 1996; Atwood et al., 2001). Feeding to satiety decreases the responses of hypothalamic neurons to the sight and/or taste of a food on which the animal has been satiated, but leaves the responses of the same neurons to other foods on which the animal has not been satiated relatively unchanged (Rolls et al., 1986).

A diversity of flavors contributes to enhanced animal welfare because generalist herbivores exposed to diverse arrays of feeds have less likelihood of experiencing stressful situations, like frustration due to lack of food alternatives available to build a balanced diet (Villalba and Manteca, 2019), or satiety due to repeated or excessive orosensorial exposure to the same single feeds (Villalba et al., 2010; Catanese et al., 2012). Consistent with this notion, a diversity of food items offered to sheep early in life reduces plasma cortisol (a hormone involved in stress responses by mammals) levels (Villalba et al., 2012; Catanese et al., 2013), lymphocyte counts (Catanese et al., 2013) and stress-induced hyperthermia in open field tests (Villalba et al., 2012) relative to animals fed monotonous rations early in life.

Knowledge Gaps

Despite the emerging findings described above, key information is still lacking regarding the chemical characteristics of different forage constituents that may contribute to specific effects of forages on the animal's internal environment and on potential chemical interactions when multiple forages are ingested. For instance, it is still unknown whether some less-explored constituents of forages such as neutral detergent soluble fiber and other non-structural or non-fiber carbohydrates (Hall et al., 1999) vary in concentration or in composition in response to different biotic or abiotic factors, or on how these carbohydrates interact with other chemicals like PSMs. Breeding programs or managerial interventions (i.e., defoliation frequency), or ecological conditions (i.e., climate, elevation), may influence the concentration or composition of these compounds. In turn, some of these changes may contribute to enhance chemical associations among forages and thus impact some key variables like the efficiency of nitrogen utilization by ruminants. The same can be said about the concentration, composition and chemical affinities of some PSMs like phenolic compounds (Mueller-Harvey et al., 2019), information that will be key for promoting (i.e., through breeding programs or management) forage characteristics that enhance interspecies synergies. Finally, a broader database is needed regarding forage and chemical complementarities like those described by Lagrange et al. (2020) on the combined effect of two tanniferous legumes at reducing urinary nitrogen excretions. This broader knowledge base could be applied in different ecoregions under different environmental conditions and with potentially greater synergistic effects when different species or a broader number of combinations are assayed.

RUMINANT PRODUCTION AND PHYTOCHEMICAL DIVERSITY

Based on the beneficial impacts on animal nutrition, welfare and health, it is expected that there would be a positive effect of phytochemical diversity on animal production at the individual level. Diverse phytochemically rich pastures often provide a more nutritious diet compared with monocultures, leading to enhanced forage intake and animal nutrition. Higher per head milk production was observed when cows grazed on complex forage mixtures compared to simple forage mixtures (Totty et al., 2013; Jonker et al., 2019). Similarly, per head milk volume and composition (milk protein, milk fat) was greater for cows grazing on pasture mixtures (*Lolium perenne*, *Trifolium repens*, *Plantago lanceolata*) or spatially adjacent monocultures of the three forages than in *L. perenne* monoculture (Pembleton et al., 2016). The authors attributed treatment differences to improved nutrition and increase in forage intake of cows grazing on diverse pastures. Experimental evidence also indicates that forage species diversity increased food intake in sheep, especially at the latter phase of the meal (Wang et al., 2010; Feng et al., 2016). Improved sheep, goat and cattle performance has also been reported in mixed grass-legume swards relative to monocultures (Rutter, 2006; Chapman et al., 2007), and in heifers grazing combinations of three different legumes relative to legume monocultures (Lagrange et al., 2020). However, other authors have reported similar per head milk production when cows grazed simple vs. complex forage mixtures (Wedin et al., 1965; Sanderson et al., 2004; Soder et al., 2006). Likewise, increments in species richness of temperate pastures (three, five, or eight forage species) did not influence cow-calf performance (Tracy and Faulkner, 2006).

Forage allowance at plant species level may explain the aforementioned differential ruminant performance in response to pasture diversity. For instance, milk production per cow in ryegrass-clover mixtures was lower when the clover represented 25% total dry matter available than when it represented 50% or 75% of the total dry matter present (Harris et al., 1997). Another possible explanation for the variable ruminant performance in response to complex forage mixtures is that species identity, or chemical identity of PSMs, is more important than the complexity of the mixtures (Deak et al., 2007). As described before for medicinal effects (section Diverse Diets: Plant Secondary Metabolite Intake and Medicinal Effects), it is important to understand the nature of the species interactions on a case-by-case basis. This idea is represented in a study where interactions between legumes and grasses could be either complementary or non-complementary, depending on species identity. A combination of *Trifolium repens* and *Schedonorus pratensis* had a positive additive effect on forage digestibility, which was not observed for a combination between *Medicago sativa* and *Phalaris arundinacea* (Brink et al., 2015). Moreover, even within a single forage species, genotypic diversity can exert strong influences on herbivore performance (Kotowska et al., 2010). A large-scale metabolomics study in *Lolium perenne* allowed the identification of high- and low-sugar genotypes (Subbaraj et al., 2019) with implications for variable interactions among forages. Since sugar content is directly and positively related with metabolizable energy and protein capture and supply in ruminants (Richardson et al., 2003; Jacobs et al., 2009), it should be expected that there would be a greater positive additive effect on animal production of high than low-sugar genotypes when associated in mixtures with high-nitrogen legume species. Plant secondary metabolite concentration may also vary among genotypes, as high- and low-tannin content varieties have been identified within different legume species (Donnelly et al., 1971), with potential to impact complementarities and synergies among forages.

Finally, climatic conditions also influence the concentration of biochemicals in forages, which may also influence synergisms and complementarities among forages. Water deficit inhibits photosynthetic activity in plant tissues, owing to an imbalance between light capture and utilization (Reddy et al., 2004), a dysfunction that leads to the generation of reactive oxygen species. In turn, plants have mechanisms of reactive oxygen species detoxification, with some of them involving flavonoids and phenolic compounds like tannins, which are antioxidant (Gourlay and Constabel, 2019). Thus, at least some phenolic compounds in plants are expected to increase their growth under water deficits (Popović et al., 2016). Water stress also reduces the rate of plant maturation (Wilson and Ng, 1975), with increments in the concentration of non-structural carbohydrates in the cell contents of forages like birdsfoot trefoil, sainfoin, white clover (*Trifolium repens*) and perennial ryegrass (*Lolium perenne*) (Kuchenmeister et al., 2013). Temperature has a strong influence on plant growth, development and chemical composition (Buxton, 1996). Lignin synthetic enzyme activities increase in plants in response to increasing temperature (Buxton and Fales, 1994), while high proportions of non-structural carbohydrates are metabolized into structural carbohydrates (Deinum and Knoppers, 1979).

Collectively, a broader knowledge base on interactions among multiple forages and chemicals—from *in vitro* to field studies- will allow for making more accurate predictions about potential synergies in order to create the next generation of functional pasturelands (see section Designing Diverse Agricultural Pastures). Another knowledge gap that needs to be bridged entails a better understanding on the impacts of environmental factors on plant chemistry and their implications for interactions among forages consumed in diverse diets.

DESIGNING DIVERSE AGRICULTURAL PASTURES

This review argues that plant diversity has the potential to enhance ecological services in pasturelands such as animal nutrition, health and welfare, while reducing environmental impacts. Nevertheless, pasture diversity is not simply a numbers game of mixing and sowing as many forage species as possible (Sanderson et al., 2007). Kinds and amounts of different forages along with their spatial arrangement and use in time are key variables that need to be considered when designing diverse and multifunctional pasture communities. The first step in undertaking this endeavor entails selecting the forage species and numbers that satisfy specific system goals (e.g., forage production, biodiversity, animal production) (Hobbs and Morton, 1999; Sanderson et al., 2007). Then, managers should ask (1) whether the species selected can tolerate the expected environmental conditions (e.g., soil characteristics, climate, plant-plant competition), (2) if the species should be planted in mixes or in blocks (e.g., spatial arrangement, architecture of the landscape or chemoscape), and finally they should (3) develop an adaptive management plan (e.g., through grazing management) incorporating long-term monitoring (**Figure 1**). In what follows, we explore some ideas regarding the design of the next generation of multifunctional pasture communities under the context of the aforementioned questions and tasks, with the aim of stimulating new research on the gaps in knowledge identified during the process.

Species Identity

Given our current state of knowledge, it can justifiably be argued that species identity (taxonomy at the level of species/cultivars) to design diverse agricultural pasture systems is critical for pasture productivity and stability as well as for animal performance and environmental impact. Although pasture productivity/ stability is beyond the scope of this review, we will briefly refer to essentials in selecting species to improve productivity and stability of agricultural pastures.

The benefit of plant diversity on productivity and stability is well-documented for natural communities (Lehman and Tilman, 2000; Isbell et al., 2009); however, it is equivocal for agricultural pasture systems (Jing et al., 2017). The most parsimonious possible explanation for the ambivalent responses in agricultural pastures is inadequate selection of species identity. Adequate selection of species represents a big challenge in designing diverse pastures (Tracy et al., 2018). This is because most diverse communities in pasturelands tend to become dominated by one or two species over time (Tracy and Sanderson, 2004; Sanderson et al., 2007; Skinner and Dell, 2016), making monitoring a key task for understanding the compositional "trajectory" of the designed pasture over seasons and years. This scenario suggests the convenience of the management of a few select species (e.g., grass/legume combinations) in order to improve resilience and other ecosystem functions (Tracy et al., 2018). Adequate species selection is also critical in the face of climate change, as it should consider the utilization of diverse mixtures that have the potential to be productive during more challenging climatic scenarios like the predicted increases in ambient temperature, drought and elevated concentration of atmospheric CO_2. Diverse agricultural pastures, better adapted to changes in environmental conditions, will be those composed of species varying in tolerance, and thus responses to changes in different climatic parameters. Functionally diverse plant communities typically exhibit greater temporal stability of productivity, than do their counterparts composed of fewer functional groups (Yachi and Loreau, 1999). Thus, a high diversity of cultivated forage species, high intraspecific genetic diversity, and the use of species and variety mixtures have been proposed as a means to enhance productivity and resilience of grasslands in the Mediterranean and Nordic regions challenged by unstable and uncertain climatic conditions (Ergon et al., 2018). Identification of moderately diverse, site-specific grass-legume mixtures and greater use of complementary forage species such as C3 and C4 grasses in order to lengthen the grazing season and provide a buffer against weather variation have also been proposed as strategies to improve the resilience of pasturelands facing changes in climate (Tracy et al., 2018). From the animal perspective, detoxification pathways are thermogenic and PSMs uncouple mitochondrial oxidative phosphorylation, which also generates heat (Beale et al., 2018). Thus, increased ambient temperatures may cause selection of diets with lower content of PSMs (Beale et al., 2018) from pasturelands of declining crude protein content (Craine et al., 2016). Therefore, associations of forages that enhance the efficiency of protein use (i.e., through a balanced provision of non-fibrous carbohydrates or condensed tannins) may be needed in predicted warmer environments.

Besides productivity and stability in production, species identity selection needs to consider improvement in animal performance while reducing environmental impact. The fulfillment of this objective requires the adequate harnessing of phytochemical diversity of both primary and secondary metabolites. Like plant production responses to diverse forage mixtures, animal performance in response to complex mixtures has also been equivocal (see previous section) which was explained through different degrees of complementarities among species identity. Complementary arises not only due to nutrient-nutrient interactions (e.g., carbohydrates-protein) that better match nutrient intake with nutrient demands, but also due to nutrient-PSMs and PSMs-PSMs interactions, as described under section Diverse Diets: Nutrients, Plant Secondary Metabolites and Flavors. Therefore, adequate selection of species identity from the animal side requires a profound knowledge on the chemical profile of individual forage species and interactions among their elements, in the benefit of animal nutrition, welfare, health, productivity, and environmental impact.

Some efforts have been undertaken to explore the influence of plant-plant interactions on plant chemistry and foraging behavior. Concentrations of nitrogen and of an alkaloid (ergovaline) in endophyte-infected tall fescue (E+; *Festuca arundinaceas* Schreb) were observed to be greater when the plant grew adjacent to legumes than when it grew in monoculture. In contrast, no differences in saponins or condensed tannins concentrations were found when alfalfa or birdsfoot trefoil grew in monoculture or in mixtures (Clemensen et al., 2017). The chemical composition of E+ as influenced by growing next to legumes or not also modified foraging behavior by

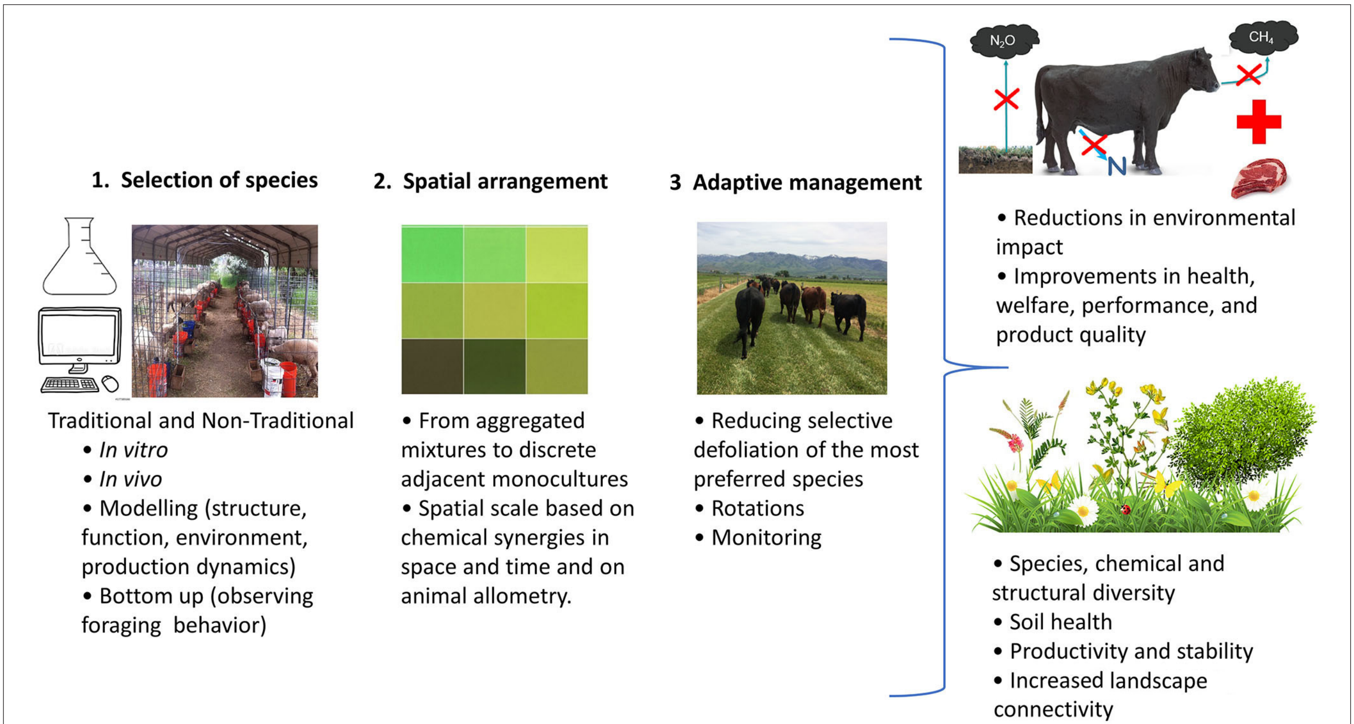

FIGURE 1 | Flow diagram for the design, benefit, and management of diverse, multifunctional pasture communities (expanded from Hobbs and Morton, 1999; Sanderson et al., 2007).

lambs (Friend et al., 2015). More research is needed on these types of interactions in order to broaden the knowledge base for an informed selection of species based on their chemical composition.

Modeling Approaches

According ecological theory, selection of forage species to create diverse agricultural pastures should be based mainly upon species productivity in the local environment as well as niche differentiation, positive interactions and differential tolerance to disturbance and stress among species. Accordingly, adequate selection of species to design diverse agricultural pastures is a process that requires a profound understanding of the structure and function of forage species and of their interactions. Because of the complexity of diverse agricultural pastures, functional-structural plant modeling represents an important tool to synthesize and integrate knowledge and to recognize research problems (Evers et al., 2019). This approach emerged from single species or growth forms, continuing with models that predicted the behavior of simple mixes considering each species separately, which represented a great complexity of inputs and outputs for highly diverse pastures (Moore et al., 1997). More recently, modeling efforts have focused on functional-structural approaches under the assumption that diverse pasture functioning can be explained by the mean value of biological attributes (i.e., functional traits) of its constituent forage groups (Jouven et al., 2006). Functional traits could be associated with production dynamics (Craine et al., 2002), environmental conditions (Diaz et al., 1998) and responses to defoliation (Louault et al., 2005). Future models should incorporate additional functional traits related to the chemical characteristics of the species, such as type and concentration of PSMs, water-soluble carbohydrates or rumen degradable protein, integrating the knowledge available on biological attributes with chemical dimensions in order to obtain more developed scenarios about the integrated benefits of diverse pastures.

In addition to functional-structural approaches, computational predictive methods have emerged in the field of novel drug discovery as time- and cost-efficient ways to explore potential chemical combinations that are successful to treat disease (Preuer et al., 2018). Drug combinations are investigated across various medical areas, such as cancer, viral disease, fungal, and bacterial infection using predictive methods that select novel synergistic drug combinations from training datasets with available information about investigational combinations (Bulusu et al., 2016; Preuer et al., 2018). A similar approach could be undertaken for pasture design based on chemical associations, with training datasets from nutrient-nutrient, nutrient-PSMs, PSMs-PSMs interactions gathered in multiple studies, in order to explore novel synergistic interactions among different forage species.

In vitro Approaches

In vitro studies have been traditionally used for screening the potential degradability and environmental impacts (i.e., through the production of CH_4 and CO_2) of single forage species (e.g., Tavendale et al., 2005; Roca-Fernández et al., 2020) and medicinal effects of bioactive-containing plants (e.g., Githiori et al., 2006) given their low cost, rapid turnaround and repeatable results. After careful assessment of the outputs obtained, the most promising candidate treatments are tested *in vivo*. Time-related gas production techniques have been extensively used to quantify the kinetics of ruminant feed fermentation (Groot et al., 1996). Gas production (e.g., CH_4 and CO_2) can be quantified and this variable is positively correlated with greater digestibility, greater energy content of the forage and potentially reduced fill effect (Blümmel et al., 2005). The technique also allows for the estimation of organic matter disappearance and fermentation efficiency (Blümmel et al., 1997). More recent studies explore *in vitro* gas production approaches using combinations of forage mixes relative to the single substrates. For instance, Aufrère et al. (2005) showed in an *in vitro* study that mixing sainfoin with alfalfa could be an efficient way to reduce the N solubility of pure alfalfa, a result that was then explored *in vivo* with positive results (Aufrère et al., 2013). Likewise, Niderkorn et al. (2011) tested grass-legume mixtures *in vitro*, showing that sainfoin can interact with different grasses to reduce the degradation of proteins and the production of CH_4 with transitory negative effects on fiber digestion. Finally, but not less important, is that in this type of studies dietary adaptation can affect substrate digestion; therefore, it should be controlled in order to avoid wrong conclusions (Gordon et al., 2002).

Bottom Up Approaches

As for the discovery of new drugs through the observation of sick wild herbivores self-selecting plants in nature (Huffman, 2003), it may be possible to learn more about synergistic forage combinations by observing how ruminants select their diet from diverse pasturelands. This approach has been applied into the design of grass-legume mixtures at biomass availabilities that reflect the preferred proportion selected by the target animal in free-choice scenarios (Chapman et al., 2007). Sheep and cattle grazing perennial ryegrass –white clover pastures, consistently prefer clover over ryegrass in a 70:30 ratio (Rutter, 2006). Thus, plant species availability is planned based on such proportion learned from the animals' preference (Chapman et al., 2007).

In a recent study, lambs were offered all possible 2-way and a 3-way choices among sainfoin, birdsfoot trefoil and alfalfa. Animals selected these legumes in a 70:30 and 50:35:15 ratio for binary and trinary combinations, respectively (Lagrange and Villalba, 2019). Lambs showed highest preference for alfalfa, intermediate for sainfoin and lowest for birdsfoot trefoil. Subsequently, the *in vitro* ruminal degradability and gas production kinetics of different mixtures of the same legumes were assessed using the gas production technique. The proportions in the mixtures represented: (1) those selected by lambs in the previously described free-choice study (Lagrange and Villalba, 2019); (2) equal proportions (50:50 or 33:33:33 ratios for binary or trinary mixtures, respectively); and, (3) single legumes. The proportion selected by lambs exhibited greater gas production rates than equal parts mixtures (i.e., indifferent selection), and similar to alfalfa, the single forage that exhibited the greatest gas production rates (Lagrange et al., 2019). Thus, lambs built diverse diets that maintained fermentability values as high as pure alfalfa while ingesting a diverse diet with some bioactives (e.g., condensed tannins) with benefits to the internal and external environment such as reduced bloat and ammonia formation, as well as the described advantages related to dietary diversity and amelioration in sensory-specific satiety. More studies like this one may contribute to generate a knowledge base that allows for the construction of diverse and chemically functional pasturelands that enhance animal performance and welfare while reducing environmental impacts.

Species Spatial Arrangement

Forage species in diverse landscapes can be arranged in spatially aggregated mixtures or discrete adjacent monocultures. Both arrangements present advantages and disadvantages. Mixtures may allow for the expression of niche differentiation and plant positive interactions (Tilman et al., 2001; Isbell et al., 2009; Clemensen et al., 2017), but hinder the maintenance of stable pasture composition (Sanderson et al., 2007) (although see next section Grazing Management), and the application of species-specific management like fertilization and weed control. As food preference in herbivores is not random, time is lost while animals search for and handle preferred food items in a finely grained mix of forage species. These activities inevitably reduce harvest efficiency with declines in forage intake and increases in grazing times (Chapman et al., 2007). The potential advantages and disadvantages of mixtures become potential disadvantages and advantages, respectively, in spatially segregated and adjacent monocultures. Studies offering animals the choice of alternative forage species such as ryegrass and white clover growing side-by-side, rather than sown as a conventional intermingled mixture, have provided evidence that animal performance benefits from the patchy spatial arrangement (Nuthall et al., 2000; Cosgrove et al., 2001). When grass and clover are planted in strips, as opposed to homogeneous mixtures, intake of forage by sheep increased by 25% (265 g/sheep/d) and milk production by dairy cows increased by 11% (2.4 kg/cow/d) (Cosgrove et al., 2001). In contrast, per cow milk production in early lactation was similar between diverse forages mixture and spatial adjacent monocultures (Pembleton et al., 2016). These differences may be related to the foraging costs of handling and searching for preferred pasture species in mixtures (Thornley et al., 1994). It is advantageous for ruminants to forage on patches when the preferred vegetation is aggregated as handling and searching activities are lower than when plants are intermingled in a mix (Dumont et al., 2002). When searching costs are low, because preferred plant species are abundant and can be encountered frequently and/or the spatial scale of separation among species facilitate finding, total forage intake in mixtures and spatial adjacent monocultures should be similar (Dumont et al., 2002). For example, a critical spatial scale of separation of grass and clover of 12–36 cm prevents beef heifers incurring selection costs (Rutter et al., 2005). In addition, planting forages in strips overcomes many difficulties inherent in establishing and maintaining mixed pastures, and also mimics what happens naturally as different plant species aggregate in response to environmental conditions (Chapman et al., 2007).

Trade-offs between spatially aggregated mixtures or segregated and adjacent monocultures in plant species interactions and plant-animal interactions can be controlled to some extent by modifying the spatial separation between monocultures, from narrow to wider strips (Sharp et al., 2014). Narrow strips may facilitate forage species establishment and allow the expression of plant complementarity (in the use of plant-growing resources) and plant positive interactions, while reducing searching foraging cost and maintaining high daily forage intake. The relative scale for "narrow" or "wide" depends on the size of the ruminant. For instance, spatial foraging strategies by sheep and cattle differ, with larger-sized cattle exhibiting a much coarser-grained use of a diverse landscape, and lower levels of patch selectivity when patches become smaller than 10 m^2 (Laca et al., 2010).

As part of the spatial arrangement of diverse agricultural pastures, it may be beneficial to establish monoculture strips of plant species containing specific bioactive compounds. Forb and shrub species contain PSMs with varied properties for the health and wellbeing of ruminants and positive effects to the environment (Vercoe et al., 2009; Monjardino et al., 2010). For instance, some shrubs and forbs have anthelmintic properties (Kotze et al., 2009), influence nitrogen metabolism with benefits to the animal and the environment (Patra, 2010), attenuate or prevent toxicity by molecular binding (Rogosic et al., 2006, 2007), represent a significant source of vitamins (Salem et al., 2010), have a positive effect on gut function (Vercoe et al., 2009) and counteract bloat caused by legumes like alfalfa by forming stable complexes with soluble protein in the rumen (McMahon et al., 2000). In addition, shrubs contribute to extend the grazing season and tolerate grazing during extended dry periods and in marginal soils, since they provide green and bioactive edible plant material where a 'feed gap' would otherwise exist (Emms et al., 2013). Woody species could also be included in diverse pasture systems as live fences, used in agroforestry for biodiversity conservation because they supply habitat for native species and increase connectivity in the landscape (Pulido-Santacruz and Renjifo, 2011). Finally, shrubs contribute to the structural diversity of the vegetation, which is significant for the maintenance of habitats for terrestrial wildlife species in agricultural landscapes (Sullivan and Sullivan, 2006). With appropriate training, ruminants can learn the use of species with bioactive compounds that cause positive post-ingestive consequences (Wallis et al., 2014).

Grazing Management

The mixture ryegrass-clover is one of the most commonly used in temperate environments around the world. However, clover presents limitations due to its low proportion in the pasture mix (typically < 0.20), its patchy spatial distribution and temporal variability (Chapman et al., 1996; Edwards et al., 1996; Fothergill et al., 1996). These limitations have been attributed to the metabolic costs of nitrogen fixation, interspecific competition, high preference by grazing animals and patchy dung and urine deposition, characteristics that are linked at least in part with grazing management of the mixture. In fact, grazing management and climatic conditions are the key factors that more strongly influence grazing system productivity (Tracy et al., 2018). Continuous selective grazing has been claimed as the main cause of reduced abundance or disappearance of preferred species in pasturelands (Parsons et al., 1991).

In contrast to continuous stocking, intensively adaptive management of rotational grazing, through reducing selective defoliation of the most preferred species, may contribute to stabilize the botanical composition of diverse agricultural pastures. In this type of grazing management, there is a tight control on stocking density, residency time and rest period in each grazed area, which contributes to the persistence of the different species in the plant community (Teague et al., 2011). These controls point to shorten the residency time to avoid grazing the regrowth, and to provide forage species with an adequate rest period for full physiological recovery. In addition, targeted animal rotations among different forages may allow for synergies among species as the sequence of forage ingestion influences intake and interactions among nutrients and PSMs with implications for animal health and performance (Mote et al., 2008; Lyman et al., 2011). Rotational grazing has been claimed to reduce per-animal production because it limits selective grazing (Briske et al., 2008); however, in diverse agricultural pastures composed by species that complement each other in primary and secondary metabolites, limitations in grazing selectivity, as discussed in section Diverse Diets: Nutrients, Plant Secondary Metabolites and Flavors, should not be expected to negatively impact animal production on a per animal basis.

CONCLUSIONS

Much of the research effort on diverse agricultural pastures has been limited to measure pasture and animal productive responses. Following a more holistic approach, our review contributes to provide new insights into pasture-base ruminant production systems through expanding the conception of the role of plant and phytochemical diversity on animal function and environmental impact. What emerged as critical consideration in the creation of diverse phytochemical pastures for proper animal function and environmental care is the incorporation of genotypes with primary and secondary bioactive metabolites that either by themselves or through their interactions improve nutrition, welfare and health of ruminants, whilst reducing negative environmental impact.

Given our current state of knowledge, it can justifiably be argued that plant diversity and the inherent phytochemical diversity represent a fundamental biological need for efficiency of nutrient use, animal performance, welfare and health (**Figure 1**). Thus, the final goal of diverse functional pasturelands is the design of more productive and stable plant communities with appropriate associations that promote synergies and complementarities among forage species that enhance these services. Management efforts in the design of diverse pasturelands up to the present have been limited to combination of grasses, legumes and forbs from "traditional" species that historically have been used in grazing systems. The challenge ahead entails the design of diverse agricultural pastures by selecting species identities from a wider array of forage options, exploring "non-traditional" forage species like cicer milkvetch (*Astragalus cicer* L.), small burnet (*Sanguisorba minor*), hairy vetch (*Vicia villosa* Roth), forage radish (*Raphanus sativus* L.), safflower (*Carthamus tinctorius*) (Meccage et al., 2019; Stewart et al., 2019; Roca-Fernández et al., 2020) and shrubs like saltbrush (*Atriplex* spp.) (Pearce et al., 2010), *Leucaena leucocephala*, *Guazuma ulmifolia* (Casanova-Lugo et al., 2014), or *Tricomaria usillo, and Mimosa ephedroides* (Egea et al., 2016). Even if these species represent a small component of the diet, the provision of plant bioactives or other nutrients (i.e., vitamins, minerals, aromas) to the internal environment may represent a significant contribution to the nutrition, welfare, and health of the animal.

A broader knowledge base regarding nutrient-nutrient, PSMs-PSMs and nutrient-PSMs interactions is needed to build the "puzzle" of species selection to be grazed not only in a spatial but also in a temporal scale, understanding potential synergisms and complementarities. The concept of developing a forage chain (Garcia et al., 2008; Cosentino et al., 2014) could be applied to the design of new multifunctional pasture communities. Forage chains provide forage at its peak of production and nutritive value to livestock over an extended period of time to take advantage of the natural growth-distribution differences existing among forage species and varieties. In this new scenario, emphasis should be given not only to biomass production and quality, but also on the presence of PSMs, flavors and nutrients that effectively complement a grazing cycle from rotations across forages at temporal scales shorter than days or seasons. Experimental evidence shows that the sequence of forage ingestion in grazing rotations that entail short periods (just hours) influence forage intake and preference in sheep and cattle (Mote et al., 2008; Lyman et al., 2011). Temporal rotations among diverse forage species are being applied successfully by sheepherders in France to create meal sequences during the day to stimulate intake and optimize use of forage diversity on rangelands (Meuret and Provenza, 2015).

A knowledge base of interactions among traditional and non-traditional species should be implemented by scaling up from *in vitro* tests to modeling and computational predictive methods, to controlled feeding trials (i.e., cut-and-carry approaches) (e.g., Lagrange and Villalba, 2019), and then to small scale and then large scale field trials (e.g., Lagrange et al., 2020; **Figure 1**). In addition to species identity, proportion and spatial arrangement of species need to be planned based on the available knowledge of the morphology, ecophysiology, biochemistry and preference of forage species under grazing conditions, as well as on the allometry of the animal species that will graze the forage mix. In the end, all these principles will allow for the design of functional and stable diverse pasturelands. Finally, but not less important, adaptive management of the forage resource through controlled grazing and monitoring would contribute to the persistence and productivity of the newly designed diverse agricultural pastures.

AUTHOR CONTRIBUTIONS

RD and JV conceived the review and acted as leading authors. JA and SL brought in specific expertise and contributed to the writing of the manuscript. All authors contributed to the article and approved the submission version.

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Urban Foodscapes and Greenspace Design: Integrating Grazing Landscapes Within Multi-Use Urban Parks

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Since the early 2000s an increasing number of planning and design projects, within the spatial design fields of landscape architecture and urban design, have focused on food landscapes and their re-integration into the urban environment; particularly as a result of recent global movements toward creating more sustainable cities and human settlements. This article explores the potential contribution of grazing lands within cities of the Global North as a multi-beneficial layer in public greenspace design. Plant-based urban farms and community gardens have experienced significant growth within developed nations in recent years, in both scholarship and practice, however the design and implementation of integrated grazing lands within the urban zone has been largely left out. For much of the Global North animal agriculture is still considered primarily rural. This research considers the potential of integrating grazing lands within the city through multiuse greenspace design, and undertakes a case study design critique of Cornwall Park, Auckland where since 1903, the Park has provided urban grazing for sheep and cattle, alongside other land uses and experiences such as recreation, heritage, bio-diversity, and education. Undertaking a "descriptive critique" of Cornwall Park, and its 100 Year Master Plan, this research is intended to enhance, the understanding and role, grazing animals can play within public greenspace.

Keywords: greenspace, public park, urban agriculture, animal agriculture, grazing lands, urban food system

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INTRODUCTION

As a basic essential for life, food has always been a critical part of any city including its production, movement and transportation, distribution, places of consumption, and waste (Pothukuchi and Kaufman, 1999, 2000; Steel, 2008, 2012, 2020; Viljoen and Bohn, 2014; Parham, 2015). The spatial relationship between food production and urban settlements has been critical in the development of cities and civilizations throughout the world, and the design and provision for spaces that allowed farming and agricultural practices to occur have been part of cities since they first developed over 10,000 years ago. Being considered an essential infrastructure, urban, and peri-urban based agriculture was integral to the success of cities globally throughout history (Pothukuchi and Kaufman, 1999, 2000; Viljoen, 2005; Steel, 2012, 2020; Morgan, 2014; Viljoen and Bohn, 2014; Parham, 2015; Kasper et al., 2017). With the advent of railways, however, in the nineteenth century, many cities of the Global North were essentially liberated from the spatial constraints of the traditional geography of such things as food production and walkability, making it possible to build and extend urban settlements that were less constrained by size, shape, and location (Steel, 2012). With many cities in the Global North today relying on long and complex food supply chains, understanding around the localization of food production and access within urban settlements has grown in recent years (Pothukuchi and Kaufman, 1999; Morgan and Sonnino, 2010; Opitz et al., 2016). This paper looks to expand the existing scope of urban agricultural research, usually focused on plant-based production, focusing instead on the design of grazing land for animal husbandry and meat production within urban greenspaces. Using a case study methodology, that includes site and document analysis, this research explores, using a depictive criticism approach, the design of Cornwall Park, and its "100 Year Master Plan" design document, analyzing how a working beef and sheep farm can be successfully integrated within a city context. Cornwall Park provides an example of the multifunctional dimensions of integrating agriculture, in particular grazing lands for livestock, in a multi-use public park alongside other land uses and experiences such as ecology, aesthetics, heritage, recreation, bio-diversity, and education.

With current concerns around climate change, environmental quality, and the health and well-being of urban residents at the forefront of city planning, the practice and development of urban food landscapes is recognized as essential to the long-term sustainability of urban settlements globally (Pothukuchi and Kaufman, 1999; Viljoen, 2005; Morgan and Sonnino, 2010; Duany and DPZ, 2011; Morgan, 2014; Opitz et al., 2016). Discussed by Duany and Talen (2002), the "urban zone" consist of four zones along the rural—urban continuum, namely the "sub-urban," "general urban," "urban center," and "urban core" zones, characterized by levels of increasing residential and built infrastructure density, increasing levels of mixed use development (including residential, retail, offices, entertainment, cultural, and public open space), and increasing maximum building heights (Duany and Talen, 2002). When considering the rural-urban transect, these urban zones are in addition to two rural zones—namely "rural preserve" and "rural reserve" (Duany and Talen, 2002, p. 255). In response to the growing environmental, climate and urban well-being concerns, various food movements have advocated strategies for re-spatializing food systems, including reducing food miles with shortened supply chains, and embedding farming in local urban ecologies (Feagan, 2007). Since the early 2000s, "urban agriculture," defined by Mougeot (2006) as *"the growing, processing, and distribution of food and non-food plant and tree crops and the raising of livestock, directly for the urban market, both within and on the fringe of an urban area"* (Mougeot, 2006, p. 4), has significantly transformed the fundamental notion of the city once again, by inverting the urban/rural dichotomy of the Global North by re-inserting food production back into parks, vacant lots, and rooftops within the urban zone. Urban animal agriculture, however, has not been widely included in the contemporary rise and interest in urban agriculture seen recently within developed nations. Today however, with increased interest in urban resiliency and sustainable food systems, spatial planners, and designers are seeking to re-accommodate animal agriculture into urban settings within the Global North, alongside the more common plant-based practices. Although cattle and other grazing stock have been used in regional parks and public rangelands both in New Zealand and internationally, the inclusion and integration of grazing stock in public urban parks has not been widely implemented, with policies around animal husbandry within urban limits of the Global North proving a significant barrier to providing space and facilities for grazing animals within cities.

Public greenspaces in cities play a critical role within the urban environment, and throughout history have fulfilled many functions from providing space for decorative public gardens and the curating of botanical species during the eighteenth century, to providing fresh air for invalids and tuberculosis sufferers in the nineteenth century, and for the communal production of food during the twentieth century World War's (van Leeuwen et al., 2010, pp. 20–21). The public park is one of the most recognizable typologies within the urban environment and is an indispensable element of urban quality, providing amenity and services to both urban residents and environmental systems. As Parham and Abelman (2018) discuss, urban parks provide an example of an urban typology with food space potential (p. 412). The various functions of urban greenspaces show that they have a complex and multidimensional structure, containing important ecological, social, and economic values that contribute to the overall sustainability and quality of life for urban dwellers (van Leeuwen et al., 2010, p. 21). Recently focusing on functioning as places for passive and active recreation, urban greenspaces are seen as multi-use providing spaces not only for recreation, leisure, rest, and relaxation, but also places for urban biodiversity, wildlife habitat, stormwater management, urban cooling, and increasingly, urban food production (Morgan, 2014).

Since the early 2000s, the practice and implementation of urban agriculture within publicly-owned greenspaces has grown in both location and scale, moving from a peripheral position within local government and urban design disciplines to one that is seen as a viable and progressive way forward for cities of the Global North to meet urban resilience agendas, increasing residents access to fresh nutritious food, and supporting human relationships with the land (Viljoen and Bohn, 2005; Mougeot, 2006; Morgan and Sonnino, 2010; Morgan, 2014; Parham, 2020). As discussed at length by authors such as Morgan and Sonnino (2010), Morgan (2014), Parham and Abelman (2018), Viljoen (2005), Viljoen and Bohn (2005, 2014), Viljoen et al. (2015), and Pothukuchi and Kaufman (1999, 2000), urban agriculture makes a positive contribution to food security, food safety and energy savings by shortening the chains that distribute food. "*Immediate advantages such as freshness of fruit and vegetable, better choice of high quality meat products and simple processes for food traceability all mark a new trend in urban consumption and behavior*" (van Leeuwen et al., 2010, pp. 21–22). Including a diverse range of activities from the cultivation of fruit and vegetables, medicinal plants, spices, and mushrooms, as well as the production of eggs, milk, meat, and wool, urban agriculture within public parks can also contribute to a reduction in maintenance cost (with the use of grazing animals, or the inclusion of food forests for example), and diversification of income streams (Mougeot, 2006; Morgan, 2014). The integration of urban agriculture into densely populated areas also greatly extends the opportunities for combining food production with the ecological and social functions of urban greenspaces. Offering an alternative land use for integrating multiple functions within city limits, urban agriculture can contribute a high degree of multifunctionality to urban environments (Viljoen and Bohn, 2005, 2014; Morgan, 2014; Viljoen et al., 2015; Parham and Abelman, 2018). In addition to the production of food, urban agriculture offers a wide range of associated benefits including ecological functions such as biodiversity and nutrient cycling; and cultural functions, for example, physical exercise, education for life skills, and social interaction and inclusion.

Design professions such as landscape architecture and urban design can play a critical structural role in developing "healthier" cities, responding to, as Potteiger (2013) discusses, public health problems and their solutions. He suggests, in the nineteenth century pathogens were identified as the primary cause of death in many European cities and thus became the central focus of public health. Contaminated wells were recognized as sources for the spread of contagious disease, and this realization led to the design of city water and sanitation infrastructure throughout the world, stating, "*since the mid-20th century, the public health paradigm has shifted from a singular focus on infectious disease to a focus on chronic illness—heart disease, cancer, diabetes, and high- blood pressure—diseases in which diet as well as environment and behavior play a critical role*" (Potteiger, 2013, p. 264). It follows therefore, that urban planning and design can play an important role in solving current public health problems through the design of cities that promote healthier lifestyle, a sense of community, and better nutritional options (Morgan, 2014). The integration of food landscapes within urban form therefore, could aid in many of the contemporary health issues, both mental and physical, being faced by our urbanizing, aging population. Offering multiple benefits to surrounding residents, the integration of agriculture into urban environments improves access to fresh and nutritious food, and in doing so can play an important role in combating obesity, diabetes, and poor nutrition, as well as supporting mental health and well-being (Potteiger, 2013, 2015). Residents can participate in urban agriculture through, for example, involvement in community gardening, school gardens, urban orchards, food forests, or farmers markets. Urban agriculture can also provide a community with access to rare foods that support their cultural customs, or heritage varieties not sold by the larger export-orientated producers.

The inclusion of animal husbandry as part of urban agriculture practice, although being an integral part of urban living in the past, has been actively planned out of many cities within the Global North over the last 100 years. Animal agriculture once provided many cities of the Global North with waste management and transportation, in addition to an important food supply. The spatial relationship between rural and urban was a continuum where food production was a visible and vital component of urban systems as well as rural (Brinkley and Vitiello, 2014). However, as cities became more crowded, enabling the easier spread of disease, alongside the invention of the railroad, agricultural production, especially animal agriculture, was zoned out of many settlements within the Global North.

New Zealand, a nation well-known for its primary production and agricultural culture consists of 26.8 million hectares, inclusive of off-shore islands. Of this, agriculture covers 53.4% (13.8 million hectares), exotic forestry 8.1% (2.1 million hectares), native forest 29.6% (7.6 million hectares), and "other" land (e.g., mountains, urban) 11.2% (3.0 million hectares) (Journeaux et al., 2017, p. 9). In New Zealand, animal agriculture is still today overwhelmingly considered to be a rural land use activity with vast areas of rural land supporting large-scale primary production. Animal-based agriculture is not a common practice within the urban zones in New Zealand, instead primarily operating within the rural landscape. Cornwall Park in Auckland however (New Zealand's largest city with a 2017 population of 1.66 million−35% of New Zealand's total population) provides an important case study example of an urban park facilitating multiple land uses including grazing land and animals. Using Cornwall Park as a case study, this research poses the question, how can grazing lands, for sheep and beef production, be designed within a public urban park alongside other park uses?

METHODS

A qualitative case study methodology was selected to deepen understanding of Cornwall Park, specifically the role grazing lands and animals play within it. The first step in a larger research project investigating the enablers and barriers to re-integrating animal-based agriculture within urban greenspaces of the Global North, the research presented in this paper uses a descriptive critique method to investigate the Master Plan document produced in 2014 (Boffa Miskell and Nelson Byrd Woltz Landscape Architects) to oversee the future development of the Park. Using Attoe's (1978) sub-category of "depictive criticism," within the "descriptive criticism" classification, this research sets out to enhance the understanding of grazing lands as an integrated land use within Cornwall Park. Bowring explains, "*Descriptive criticism is a category which includes writing about the designed work in factual ways, in contrast to the creativity of interpretive criticism. It is not an evaluative approach, but one which is intended to enhance the understanding of the work within its context*" (Bowring, 2020, pp. 31–32). Sitting within the classification of "descriptive criticism," "depictive criticism" aims to elucidate static or dynamic aspects of a building or landscape. "*It will be argued that depictive criticism is not criticism at all since no stand on the question of 'good' or 'bad' is taken. Buildings [or landscapes] are simply depicted*" (Attoe, 1978, p. 85). This form of criticism performs an important service by forcing attention on special aspects of the landscape and telling us to "see" them, setting up the possibility of a new experience directed by this factual approach to design criticism. Further survey-based research looking at the perceptions and attitudes of surrounding residents to the inclusion of animal agriculture within the Park is proceeding as part of the larger study, and this will be followed by interviews with residents, park users, and park management. In this first stage of research, forming a deep understanding of the site and context is key to successfully translating survey and interview data into meaningful analysis and interpretation.

Case studies are a structured way of recording design projects, and according to Francis (2001), the use of case study methodology has a long and well-established history in landscape architecture and other design disciplines, typically used to describe and/or evaluate a project or process (p. 15).

The implementation of spatial, infrastructural, and land use changes proposed by the expert-driven Cornwall Park 100 Year Master Plan, are in the early stages and, therefore, the descriptive critique of the case study outlined below focuses on the initial case study steps of investigating the spatial, historical and contemporary context; the project background and vision set by the Cornwall Park Trust Board Inc. (in conjunction with landscape architecture firms Boffa Miskell and Nelson Byrd Woltz Landscape Architects); and site analysis carried out through both site visits and the exploration of the detailed Master Plan document.

CASE STUDY

New Zealand is known worldwide for its primary food and fiber production. Agriculture is vital to the economy as well as being important in terms of national heritage and identity. Today however, the urban population exceeds 80% of New Zealand's total population, with many New Zealanders having little or no physical or social connection to productive landscapes. Providing opportunities to experience land and agricultural processes within cities is deemed increasingly important as New Zealand's population urbanizes and the spatial divide between rural and urban grows.

Tāmaki-makau-rau Auckland is New Zealand's largest city, with much of the urban extent built on lava and volcanic debris from the 48 volcanoes that comprise the Auckland landscape, within a 20 km radius. Maungakiekie One Tree Hill is one of Auckland's most iconic volcanic features [**Figure 1** illustrates the memorial obelisk at the summit of Maungakiekie One Tree Hill, with landscape terracing created during Māori occupation of this former Pa (village and fortification) site]. Having erupted 20,000–30,000 years ago, the event created a complex scoria cone with extensive lava flows. Three craters were formed during the eruptions. These three craters today form the Maungakiekie One tree Hill Domain, which borders Cornwall Park. As the city of Auckland has grown in both population and spatial extent, since 1903 Cornwall Park has provided a multi-use public greenspace where animal grazing has played, and continues to play, an important role in the maintenance, educational and heritage value of the central city landscape (Panel shows an aerial image of Tāmaki-makau-rau, Auckland, indicating the location of Cornwall Park and Maungakiekie One Tree Hill Domain within the city of Auckland Google, 2020). A site rich in Māori cultural heritage and settler agricultural history, the Park was gifted to the people of New Zealand by Sir John Logan Campbell, and now sits centrally in New Zealand's biggest city.

The land which today constitutes Maungakiekie One Tree Hill, which borders Cornwall Park, holds significant national cultural value within New Zealand—being one of the most extensive former Pa sites in New Zealand. During pre-settlement times Māori occupation of the land saw the creation of extensive terraces built primarily to house sites for food storage pits and hearths. Kumara (sweet potato) was stored for winter in pits to preserve the tubers in an even temperature and humidity. Vast areas of cultivated land around Maungakiekie supported the inhabitants with crops of kumara, yam, and taro, grown in the fertile volcanic soils that are now part of Cornwall Park (The Cornwall Park Trust Board Inc, 1994). Māori population peaked in this area during the sixteenth and seventeenth centuries, but with increasing inter-tribal warfare, saw, by the 1820's, survivors relocate to surrounding regions and districts. This was the situation as European settlers arrived in the 1840's to find no people living on Maungakiekie (The Cornwall Park Trust Board Inc, 1994). In 1853 John Logan Campbell and William Brown

FIGURE 1 | Aerial images of Cornwall Park and Maungakiekie One Tree Hill Domain showing urban context and density. Map 1: Adapted from Google Earth, Imagery ©2020 TerraMetrics, Map data ©2020 New Zealand. Map 2: Adapted from Google Earth, Imagery ©2020 Google. Map data ©2020 New Zealand (Google, 2020).

bought the One Tree Hill Estate from Irish settler Thomas Henry. In 1871, the partnership with Brown was dissolved and Campbell took over the farmland adjacent to Maungakiekie One Tree Hill Domain (Maungakiekie One Tree Hill had been taken as public reserves by a commission court set up by Governor Gray). In 1901 Campbell bequeathed the One Tree Hill estate to the people of Auckland, naming the estate Cornwall Park. Between 1901 and 1903, Campbell's main aim was to the convert the farm into a public park. He employed 20-year-old Landscape Architect, Austin Strong to conceptualize his vision. The founding principle of Cornwall Park, preserved in the Deed of Trust, dedicated the Park as a place of recreation in service to the people of New Zealand (The Cornwall Park Trust Board Inc, 1994).

For 120 years Cornwall Park has sat surrounded by a changing landscape—from farmland to suburban neighborhoods, to today sitting within a medium—high density residential urban zone. *"The land surrounding Cornwall Park has seen dramatic change, from open farmland to a popular residential neighborhood. With his gift of the lands for Cornwall Park, Sir John Logan Campbell envisioned this growth, dedicating the park as a space for recreation that he knew would be in higher demand as the city grew"* (Boffa Miskell and Nelson Byrd Woltz Landscape Architects). Cornwall Park encompasses 172 ha of public greenspace (**Figure 1** indicates an aerial image of Cornwall Park and Maungakiekie One Tree Hill Domain showing urban context and density). It is located in the Auckland suburb of Epsom, and using the work of Andre Duany, sits within the "General Urban" zone (Duany and Talen, 2002, p. 255) surrounded on all sides by predominantly medium to high density residential land, i.e., 30–50 people per hectare (Fredrickson, 2014, p. 33). In 2014, Boffa Miskell (NZ) and Nelson Byrd Woltz Landscape Architects (USA) were engaged by the Cornwall Park Trust Board to produce a 100 Year Master Plan for the Park, that would ensure its long-term future as an important urban greenspace for Auckland city (refer **Table 1** for baseline information and context, and **Table 2** for a summary of the site design details).

TABLE 1 | Baseline information/context.

Location	Epsom, Auckland	
Size	172 ha (wrapping around Maungakiekie One Tree Hill and One Tree Hill Domain)	
Client	The Cornwall Part Trust Board	
Designer	Landscape Architect Austin Strong	
Ownership	Cornwall Park—Cornwall Park Trust One Tree Hill Domain—Tupuna Maunga o Tāmaki Makaurau Authority (Maunga Authority) and Auckland Council	
Date	1903	
Land use type	Urban Greenspace—Public Park	
Landscape features	Maungakeike One Tree Hill Highly valued cultural landscapes of national importance Significant archeological sites	
Park features	Parkland, extensive historic tree plantings (exotic, native and fruit), agricultural land, historic agricultural infrastructure (stone walls), café, restaurant, discovery hub, historic cottage, memorial, rongo stone, playground, band rotunda, folly	
Underlying challenges of the site	Nationally significant pre-settlement archeological sites Important geological land formations—volcanic boulder fields Surrounded on all sides by medium-density neighborhoods Four-lane Green Lane cuts the northern precinct off from the rest of the Park	
Current Management	Cornwall Park Trust Board Park Director Finance and Administration Manager Property Manager (+ Assistant) Park Supervisor Information Center Manager (+ 2xAssistants)	Farm Manager Horticulture Supervisor Arborist x2 Parks and Recreation Manager Principle Parks and Recreation Specialist
Users	Neighbors Auckland residents Sports clubs School groups Walkers	Fitness Dog walkers Mothers with babies and young children Educational groups Event goers

The Master Plan outlines six guiding principles (refer **Table 3**) that represent the underlying values of the Cornwall Park development. Each principle is applied to the site through multifunctional approaches to landscape management, environmental stewardship, user experience, and a commitment to continue and develop the agricultural heritage legacies of this landscape. These principles, discussed and analyzed below, explore the concept of reintegrating grazing lands for sheep and beef production within a public urban park alongside other park uses, with the masterplan design (as illustrated in **Figure 2**) illustrating the spatial implementation and development of these principles.

The guiding principle of Kaitiakitanga recognizes the important role Cornwall Park plays as a regional resource, with regards to both its size, shape, and location within the wider Auckland landscape. *"As Auckland grows, the habitats within the park will become even more valuable to native flora and fauna both locally and regionally. Increasing the biodiversity within the park will enhance the overall ecological value as well as the park's resiliency to potential challenges such as disease, storms and climate change"* (Boffa Miskell and Nelson Byrd Woltz Landscape Architects, p. 14). A focus on maintaining the Park's open landscape character, alongside improving visitor experience will see ecological resources made visible and legible to visitors, providing opportunities for visitors to connect with and care for the natural ecosystems present within the Park. Together with neighboring Maungakiekie One Tree Hill Domain, the urban greenspace forms the largest parkland in Auckland city, and the Master Plan proposes to offer visitors the opportunity to engage with the Park's ecology, and improve ecological value within the wider regional network, particularly for avifauna, and to *"increase the Park's biodiversity, structural diversity and habitat*

TABLE 2 | Site design information.

	Original Park Design (The Cornwall Park Trust Board Inc, 1994)	100 Year Masterplan (Boffa Miskell and Nelson Byrd Woltz Landscape Architects, 2014)
Year	1903	2014—ongoing
Designer	Austin Strong, Landscape Architect	Boffa Miskell (New Zealand) and Nelson Byrd Woltz Landscape Architects (USA)
Vision	A public park for the rapidly growing city. A place where people would be able to escape "the hustle and bustle of the workaday world"	A Park that remains the treasure of Auckland committed to providing public places for recreation, exercise, learning, cultural expression, **connection to the land** and to nature, and strengthening the bonds of community. A Park that protects its sacred ground, celebrates heritage, and **expresses New Zealand's agricultural roots**
Goals	To turn Cornwall Park from a farm into a park. The design was intended to safeguard the "magnificence and beauty" of the parks "natural situation" while also providing for a large number of leisure activities.	Improve the park's ecological stewardship and resiliency Reinforce and strengthen the park's design and aesthetic. Aspire to beauty in all things Support preservation and active interpretation of the park's cultural heritage and history **Commit to agriculture as an important cultural legacy integral to park management** Prepare the park to continue to serve the citizens of Auckland in a dynamic future Equip the park to transform from a suburban park to an urban park
Landscape layers/landscape features	Carriage roads Grand avenue and path to the summit (of Maungakiekie One Tree Hill) Sport Agriculture Structural tree planting Shrubs and tree planting (combinations of both native and exotic)	**Agricultural precinct** Sport Precinct Core Precinct Onehunga Precinct (see further details below)
Cost of Implementation	$2,000	Unspecified
Awards		2015 ASLA Professional Award (Honor Award, and Analysis + Planning) 2017 NZILA Category Winner—Strategic Landscape Planning and Environmental Studies

TABLE 3 | Guiding Principles, Cornwall Park 100 year Masterplan (Boffa Miskell and Nelson Byrd Woltz Landscape Architects, 2014, pp. 14–15).

Kaitiakitanga	Stewardship as guardians of the deep links between humans and the natural world.
Tikanga	The principles and practices which embody and underpin the development of the park.
Tiaki Onamata	Support, protect, save, and uplift, as stewards of the park's unique history
Nga mahi ahuwhenua	**The development of exemplary agricultural practices to provide sustenance and nourishment for people and visitors to the park.**
Turangawaewae	A place to stand. The park as a place for Aucklanders to stand and have a sense of belonging.
Manaakitanga	Provide enduring support, hospitality, kindness, and vision for the park.

value with a system-wide approach that addresses planting, soil health, native food resources, and habitat connectivity" (Boffa Miskell and Nelson Byrd Woltz Landscape Architects, 2014). Care is also provided in the Master Plan for the underlying Onehunga aquifer.

Tikanga, the second principle, responds to the unique character and beauty of the park. *"All aspects of the park affect the perception of beauty and place—the combination of design, maintenance, history, natural features and the amination of its landscape by people"* (Boffa Miskell and Nelson Byrd Woltz Landscape Architects, p. 14). The Master Plan proposes that strengthening the Park's aesthetic value should be inherent in every change and adaptation.

As has been a core land use in the past, the Master Plan continues to support and grow the agricultural legacy of the Park into the future. The cultivation of food has been part of the landscape, which is now known as Cornwall Park, for as long as humans, both Māori and European (refer **Figure 3** showing grazing cattle and sheep within Cornwall Park) have inhabited that landscape. The principle of Nga mahi ahuwhenua celebrates the agricultural legacy of this place (Boffa Miskell and Nelson Byrd Woltz Landscape Architects, p. 14). Visitors experience the Park and all its uses alongside the animals (**Figure 3** showing pedestrians using the park to commute between suburbs and avoid the busy roads by creating desire-line tracks through sheep and cattle paddocks).

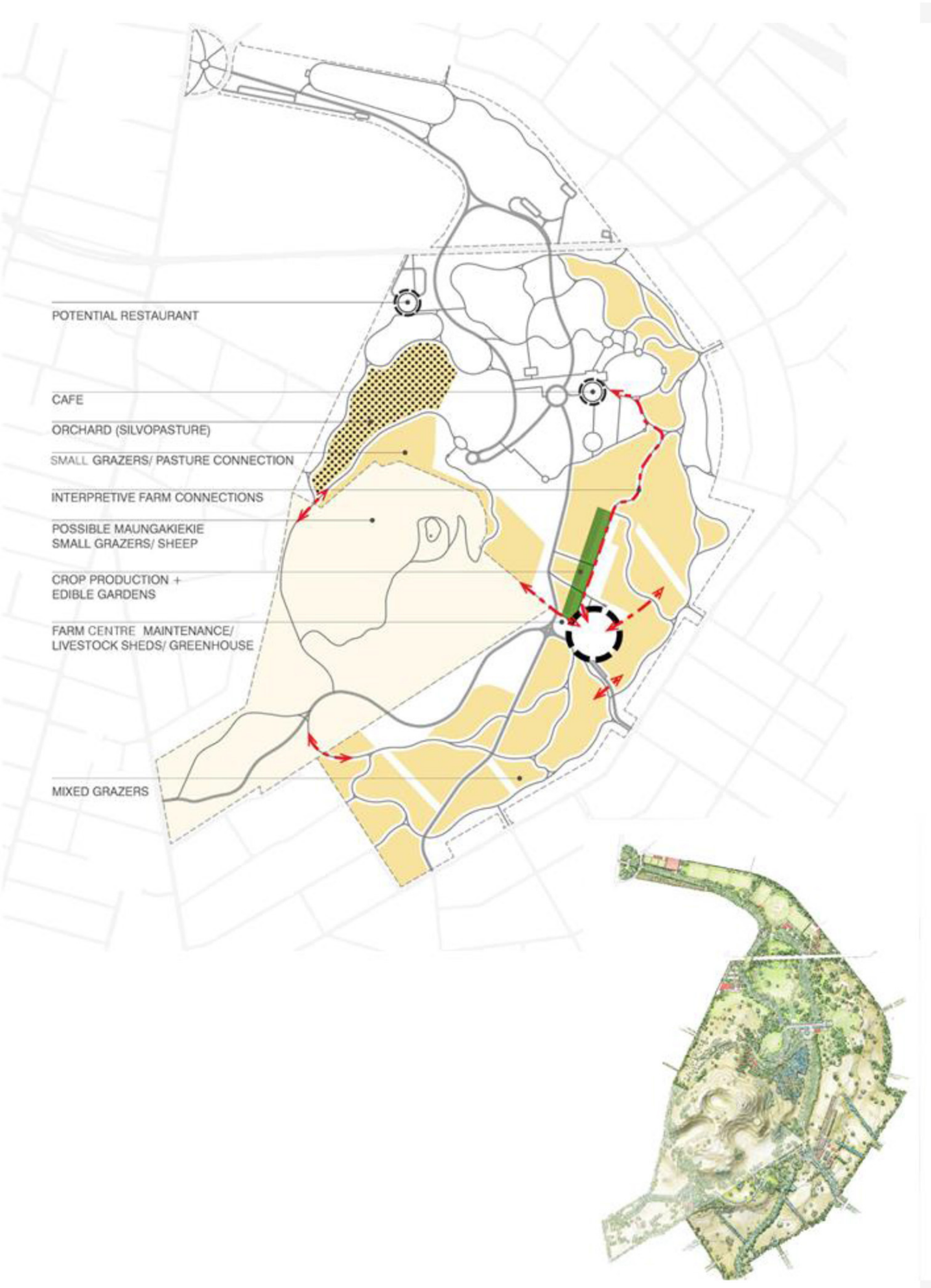

FIGURE 2 | Cornwall Park "100 Year Masterplan" by Boffa Miskell and Nelson Byrd Woltz Landscape Architects (2014), indicating proposed productive land uses/grazing lands within the Park. Source: The Cornwall Park Trust Board Inc (1994) and Boffa Miskell and Nelson Byrd Woltz Landscape Architects (2014).

Tiaki Onamata recognizes the land as a precious resource, where the geology, soils, plant, and animal life is embodied in the landscape, and where the ground is understood as a precious resource (Boffa Miskell and Nelson Byrd Woltz Landscape Architects, p. 15).

The principle of Turangawaewae is a founding principle of Cornwall Park and is a value preserved in the Deed of Trust dedicating the Park as a place of recreation in service to the people of New Zealand, and is at the core of the Master Plan vision (Boffa Miskell and Nelson Byrd Woltz Landscape Architects, p. 15). As the population around the Park changes, the Park shall adapt allowing for the changing needs of the people it serves. "*With the city and surrounding neighborhood continuing to urbanize, the next 100 years calls for a transformation of*

FIGURE 3 | Cornwall Park images, clockwise from top left: Obelisk at the summit of Maungakiekie One Tree Hill, with landscape terracing created during Māori occupation of this former Pā site; Grazing cattle within Cornwall Park surrounded by residential living; Sheep within Cornwall Park finding shade under large specimen trees; Pedestrians use the park to commute between suburbs and avoid the busy roads by creating desire-line tracks through sheep and cattle paddocks. Source: Photos by Shannon Davis.

parking space to park space and forging new public transportation connections privileging the pedestrian experience and increasing the amenity of the park" (Boffa Miskell and Nelson Byrd Woltz Landscape Architects, p. 15). The final principle of Maanakitanga responds to the need to change, support and provide an enduring vision of the Park.

Park *layers* outline and describe the multibeneficial aspects of the Park that sit within the same physical space and offer multiple functions, for example expressing landscape and cultural character, visitor experience and engagement, and function, whether that be ecological, recreation, leisure or agricultural. The *layers* described in the Master Plan include *cultural landscapes*, *agriculture*, *park ecology*, *user experience*, and *infrastructure*—activities situated in the same horizontal space, synthesizing, and working in combination to create multiple benefits across the landscape. People are invited to move through the landscape of the Park, choosing their own paths, and engaging with multiple land uses. It is only during springtime (September–November in New Zealand), when calving and lambing occurs, that visitors to the Park have limited access to some paddocks to ensure animal welfare, and human safety.

The quality of user experience is emphasized throughout the Master Plan with reference to Park aesthetics, connectivity and pedestrian orientation, upgraded Park facilities, as well as visitor education and community outreach programs. Due to the significant cultural value of Cornwall Park (and bordering Maungakiekie One Tree Hill), the Cornwall Park Master Plan proposes minimizing disturbance to the grounds of the Park, and also emphasizes the importance of preserving, protecting and adapting the historic landscape features for the long-term. It integrates "Cultural Walks" with interpretation information of the Parks rich cultural history, both pre- and post-settlement. Legacy planting is prioritized by maintaining existing historic plantings and outlines a plan for their replacement over time. The establishment of "*guidelines for farming in historic landscapes with sensitive geologic and archeological features*" (Boffa Miskell and Nelson Byrd Woltz Landscape Architects, 2014) is also proposed.

The celebration of the rich agricultural heritage of the Park is integrated by the Master Plan through the proposed farm-to-table production model, incorporating the existing livestock, with the introduction of pre- and post-European food crops, and then demonstrating the complete food story through featuring the products in the Parks cafés and proposed farmers market, and in the future, possibly a Park Farm store. Expanding the educational programs to "*include interpretation of crops, historic gardens and contemporary sustainable gardening techniques… sits alongside new pasture layout to accommodate changes in grazing regimes*" (Boffa Miskell and Nelson Byrd Woltz Landscape Architects, 2014).

The long term vision of the Master Plan sees Cornwall Park demonstrating a whole systems approach to agriculture, with production methods addressing global environmental issues and concerns (Boffa Miskell and Nelson Byrd Woltz). The Master Plan provides direction for a focus on increasing biodiversity, improving carbon sequestration, reducing use of inputs including oil and phosphates, providing innovative education and outreach, and long-term economic viability of the Park operating as a working farm (Boffa Miskell and Nelson Byrd Woltz Landscape Architects, 2014). The proposed introduction of gardens and crop production adds a new focus to the existing agriculture system, particularly with regard to the education of urban consumers—the Parks neighbors.

> In an era where urban dwellers are increasingly isolated from the production of their food, Cornwall Park can serve as an important educator by implementing a sustainable farm-to-table model. This suggests a greater diversity of agricultural products, and celebration of the land's rich gardening history (Boffa Miskell and Nelson Byrd Woltz Landscape Architects, 2014).

The Master Plan proposes five design goals for the *Agricultural Layer*: (1) exemplify best practices for sustainable farming in heritage landscapes; (2) express Cornwall Park's cultural heritage and historic agricultural endeavors through contemporary examples of agricultural production; (3) practice a sustainable, holistic approach to livestock management and plant based food production, creating an exemplary farm-to-table working farm; (4) expand educational opportunities for visitors to connect with the agricultural heritage of New Zealand; and, (5) conserve and preserve novel ecologies while supporting and nurturing native ecosystems and associations.

> Cornwall park is a place where New Zealanders can learn about their agricultural heritage. The current incarnation of livestock farming is a unique and beloved attraction that is essential to the maintenance of the park grounds. With the story of sustainable and local food production increasingly hidden from urban life, the introduction of crops and gardens can reflect the historic gardening the landscape has supported while engaging contemporary issues of local and sustainable farming (Boffa Miskell and Nelson Byrd Woltz Landscape Architects, 2014, p. 14)

The Masterplan proposes that the parkland driven, by agricultural systems, will comprise of ∼50 ha of pasture within Cornwall Park itself. Current agricultural infrastructure will be retained such as pastures, shelterbelts, specimen tree planting, stockyards and existing farm buildings, and heritage production-based elements will be preserved and enhanced, such as remaining kumara storage pits, Māori garden remnants, and the Parks original stone farm walls.

Production types will continue a cattle stud herd, lamb and wool/pelts production, and the creation of a new agricultural hub within the Park where it is proposed heritage crops and orchards will be created alongside farm-to-table vegetable beds. Diversifying production management systems and models is prioritized for the Park building greater long-term resiliency. These production systems include Management Intensive Grazing (MIG) for pastures (both cattle and sheep), where the basic principle is to utilize pasture grasses at maximum efficiency by mimicking the grazing pattern of ruminants in the wild. "*These animals move in herds at high density, grazing land thoroughly, and move regularly to new pasture. This pattern is replicated with rotations of domesticated herds using portable fencing and watering systems, closely monitoring pasture regrowth while maintaining appropriate stocking densities*" (Boffa Miskell and Nelson Byrd Woltz Landscape Architects, 2014). Silvopasturing is the incorporation of trees into pasture lands and will be used to provide multiple benefits to both animals and land, while adding to the diversity and economic resiliency of the Park. Agroforesty will be adopted and "guilds" of plant communities will be selectively developed into Park landscapes. Areas of coppicing for timber and fuel will also be developed. Several plant-animal systems will be incorporated including areas where stock and vegetable fields operate for the benefit of both, where crops such as mustards and cabbages can be grown and once harvested, residues can be grazed offering winter feed for cattle (Boffa Miskell and Nelson Byrd Woltz Landscape Architects, 2014).

It is hoped that benefits derived from the diversifying of production systems within the Park, as outlined above, will result in carbon neutral livestock farming where animals are raised on grass-based diets, and are continuously rotated increasing the capacity of the land to store carbon through building soil organic matter. Fuel reductions will be achieved through reducing or eliminating winter feed production and grazing year-round will produce more biomass and soil biological activity. The establishment of seasonal based pastures with appropriate forage species will aid the year-round grazing and contribute to the overall resiliency and health of the system. Sheep will also be used to graze parkland and lawn areas in lieu of mowing, further reducing fuel usage (Boffa Miskell and Nelson Byrd Woltz Landscape Architects, 2014). The proposal to develop vegetable production beds, potager gardens, trial plots and arbors will also support the sustainable, local food production philosophy, and the farm-to-table vision. A new Farm Center will include Park maintenance infrastructure and offices, livestock sheds and holding pens, greenhouses and potting shed, production gardens, and has the potential to host a future farmers market. The six guiding principles used in developing the vision of the Master Plan broadly—Kaitiakitanga, Tikanga, Nga mahi ahuwhenua, Tiaki Onamata, Turnagawaewae, and Manaakitanga—can be seen to inform and direct design decisions with regards to the agricultural layer within the Master Plan, and specifically with regards to the continued integration and enhancement of grazing animals.

Kaitiakitanga—stewardship as guardian of the deep links between humans and the natural world, is depicted in relation to the agricultural design layer of the Park through the commitment to grazing animals playing a vital role in the continued function, maintenance, and holistic lifecycles of ecological systems within the Park. Tikanga—the principles and practices that embody the unique character of Cornwall Park see education and growing agricultural literacy within the urban population as being a key feature to the Master Plan and is illustrated through the proposed development of an agricultural hub within the Park, along with proposed community food growing and workshops, and a paddock to plate ethos for the Park's eateries. Expanding the educational program to include the interpretation of crops, historic gardens and contemporary sustainable gardening and farming techniques is also proposed by the Plan. The principle of Nga mahi ahuwhenua, guides the goal of exemplary agricultural practice within the Park, and is exemplified by the spatial and functional strategies illustrated within the 100 Year Master Plan to provide sustenance and nourishment for people and visitors. Depicted through the commitment to holistic health and well-being of the land, animals, water, and people, this principle is elucidated functionally through the proposal and development of diverse and multi-beneficial farming practices, such as agroforestry seen within the proposed development of the Olive grove where it is re-imagined as a place where orchard planting and grazing can co-exist. The principle of Tiaki Onamata aims to support, protect, save, and uplift the preservation and interpretation of the Park's cultural history, for which agriculture, both pre- and post-settlement is integral, and is illustrated through the protecting and prioritizing of historic agrarian features within the Park landscape, such as the pre-colonial kumara (sweet potato) gardens, the kumara pits on the Maunga, and the stone walls within the Park. The Master Plan also proposes the development of guidelines for farming in a historic landscapes with sensitive geologic and archaeological features. Turangawaewae, a place to stand and have a sense of belonging is represented within the agricultural layer of the Masterplan with the continued support and provision for visitors to have wide-reaching access to the paddocks and animals, where respect and care for the animals is encouraged through enhancing knowledge and accessibility. Finally, the principle of Manaakitanga, providing the enduring support, hospitality, and kindness for the parkland and animals that inhabit it, sees the Master Plan illustrate a design decision that will see pedestrians prioritized over cars within the Park. Cars will be relocated to the outer limits of the Park, thus further protection and enjoyment of the animals enhanced.

The Plan also proposed adjustment to pasture layout, accommodating changes to more holistic grazing regimes, as discussed above.

CONCLUSION

As global urbanization continues, the retention and creation of functioning productive grazing land both within and on the fringe of urban areas globally, is under increasing pressure from land development. There has been recent interest within the spatial design professions around the re-introduction and prioritization of plant-based agriculture within urban systems through community-based and civil initiatives such as community gardens, urban allotments, food forests, roof gardens, and urban orchards. The argument for the design of all cities into the future to integrate urban agriculture as essential infrastructure responds to concerns around low impact, transparent, and accessible food. Including animal agriculture for meat production in this future has been identified as a "gap" in urban design and planning research and practice. The potential of urban greenspaces to reintegrate grazing lands and accommodate urban animal agriculture could offer a supported spatial and operational structure to re-introduce animals for food production, back into the places where people live. The lack of research and implementation currently experienced for this type of urban agriculture, however, illustrates the often complex urban contexts within cities of the Global North. Inflexible planning rules, high land values, lack of suitable space, and public perception may all contribute to the difficulties that surround the re-integration of grazing lands for animal urban agriculture within cities of the Global North.

Today, many regional and city plans promote community gardens, food forests, urban composting, and city orchards as a way to increase social interaction and the health and well-being among their residents. The case study of Cornwall Park illustrates how the integration of livestock can provide essential services to both land management and maintenance, alongside visitor education, living heritage, and local food production. The 100 Year Master Plan (Boffa Miskell and Nelson Byrd Woltz Landscape Architects, 2014) provides a vision and commitment to the ongoing integration of grazing livestock within the central city park, harnessing benefits for humans, land, and the environment. Providing local meat and wool production within the limits of New Zealand's largest city, reduced fuel usage and greenhouse gas emissions, and the opportunity for agricultural education, experience and engagement for an urban populace, Cornwall Park and its animal agriculture provides an important visible story for urban residents of local food production that is normally invisible in urban life today.

The six principles, Kaitiakitanga; Tikanga; Nga mahi ahuwhenua; Tiaki Onamata; Turangawaewae; and Manaakitanga, integrated through the Master Planning process, provide underlying values that have guided the development of the Master Plan, and will be used to guide its future implementation. Each principle provides guidance in the decision making process around the inclusion and integration of animals within this urban park setting, and the prioritization of the agrarian landscapes into the future—illustrating its importance to both the functionality and spirit of this place.

This research set out to investigate how grazing lands for sheep and beef production can be designed within a public urban park alongside other park uses. The case study site of Cornwall Park, New Zealand, illustrates an example within the Global North context of how grazing lands are integrated, utilized, and indeed prioritized in vision-setting within an urban greenspace. Located within a medium—high density suburb, within the "urban zone" Cornwall Park provides an important exemplar of integrated animal urban agriculture for the Global North, contributing to the current gap in research and practice examples within this context and setting.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

This research was carried out by SD including a review of the literature, study of the masterplan, and site visits to the case study site.

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Back to Nature With Fenceless Farms—Technology Opportunities to Reconnect People and Food

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The development and application of the fence was one of the earliest forms of agricultural technology in action. Managing the supply of animal protein required hunter gatherer communities to be able to domesticate and contain wild animals. Over the ages the fence has become ingrained in the very fabric of society and created a culture of control and ownership. Garett Hardin's article titled "The Tragedy of the Commons" suggested that shared land, typified by access to a fenceless common resource, was doomed to failure due to a human instinct for mistrust and exploitation. Perhaps the fence has created an ingrained societal cultural response. While natural ecosystems do have physical boundaries, these are based on natural environmental zones. Landscapes are more porous and resilience is built up through animal's being able to respond to dynamic changes. This paper explores the opportunity for remote monitoring technologies to create open fenceless landscapes and how this might be integrated into the growing need for humans to access animal protein.

Keywords: fence, virtual fence, technology, social licence, tragedy of the commons

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INTRODUCTION

The rise of *Homo sapiens* has seen unprecedented impacts on planet earth. The transition from small groups of nomadic hunter gathering communities to settled early agriculture marked the start of modern civilisation (Zeder, 2008). Managing landscapes to ensure a reliable food supply resulted in early domestication and tribal control of spatially important resources (Mysterud, 2010). Rather than hunting for food early agricultural practises started to control the supply of food (Zeder, 2008). This control ensured a regular supply of nutrients that were protected and could be stored. Delineating tribal boundaries that ensured domesticated livestock were accessible would have required a form of containment or fence (Mysterud, 2010). The change from group ownership and management to individual ownership and management of animals and nutrient supply, particularly in Western societies, especially Britain and her colonies, saw the rise in the use of containment or fences (hedges, drystone walls, and fences) to both keep in animals and keep out animals and delineate ownership lines. Pastoral agriculture systems differ from other forms of agriculture in that livestock are autonomous and mobile, therefore requiring containment, through training, breeding or physical barriers.

There are a wide range of contemporary grazing production systems that includes open-range domesticated livestock keeping, semi-domesticated pastoralism, and intensive fenced livestock farming systems. Estimating the current global distribution of these different pastoral livestock methods is challenging and uses coarse census data coupled with statistical models that estimate the geographical distribution. While fences are not used in all grazing systems they have played an important role in more intensive, low labour farming systems that are typical of pasture based systems in Australia, New Zealand, Europe, parts of southern Africa, North America and parts of South America.

The results of agricultural technological innovation have been far reaching (Klerkx and Begemann, 2020). For example boundaries and fences have become synonymous with identity and ownership, whether this applies to a farm or an individual house and garden or regional and national jurisdictions. The extent to which technological innovation has been driven by unique human cultural responses and the extent to which it sits within a broader natural environmental context poses many questions (Rosenberg, 1990; Gremmen et al., 2019; Fogarty and Kandler, 2020). However, current developed agricultural practises have diverged to a point where their very existence is only possible due to refined cultural practises that exploit innovation and in doing so creates ethical challenges for farmers and the broader community (Gremmen et al., 2019).

By exploring the transition of technological innovation, it is clear that unlike most natural systems that tend to evolve to optimise nutrient and energy efficiency, agricultural production has optimised labour efficiency often at the expense of energy efficiency (Pimentel and Pimentel, 2007). Humanities' ability to form cooperative social groups that desire meaning, that build stories and seek to spend time solving abstract problems has resulted in modern food supplies being delivered by small groups of farmers (Fogarty and Kandler, 2020). Efficient modern agriculture has exclusively optimised labour efficiency. In developed nations it is estimated that over 95% of the population have no direct involvement in growing food. The resultant disconnects between producing food and consuming food has created economic drivers that make it easy to mask the broader consequences associated with modern farming systems.

The "Tragedy of The Commons" explicitly speaks to selfish motivations driving individual behaviour within the context of shared resources (Hardin, 1968; Lloyd, 1980). Implicit in these articles is the broader dilemma underlying food security. While there has been debate over the validity of selfish motives driving use of shared resources (Ostrom, 1999) the analogy of livestock grazing common land talks to the desire to secure economic gain at the expense of long-term sustainability. While not essential fences do allow livestock farmers to not only contain animals but also to assign them responsibility for managing the land.

Emerging innovation in sensor networks built on the "internet of things" (IoT) is creating the opportunity for new agricultural farming practises. Rifkin talks about a move towards a third industrial revolution creating a green economy (Rifkin, 2016). Large jumps in industrialised activity have been built on synchronous advances in three key domains: energy, communication and transportation. The emerging revolution will utilise these drivers to facilitate increased democratisation and locally diverse productivity (Rifkin, 2016). We can already see the impact of these changes in areas such as education through video sharing platforms and new economic models for music sharing. The convergence of the IoT coupled with greater connectivity that empowers like minded individuals to find their tribe and collaborate from around the world could have a significant impact on how we farm.

This paper considers the role of the fence in modern industrialised farming systems and the benefits of containing livestock. There are important livestock production systems around the world that allow herbivores to graze in unfenced areas, however, this paper is focussed on fenced farms that are typical of livestock farming in Australia, New Zealand, North America, and Europe. At face value the fence is just a means to control livestock movement. However, the fence is also a metaphor for society's relationship with food production. The fence not only contains livestock but also restricts access to food production. This paper considers how the fence has led to a disconnect between growing food and consuming food. Emerging technologies are potentially shaping a new age of fenceless farming; this paper considers how fenceless farming could create new opportunities. This paper considers how remote automated livestock management technologies such as virtual fencing might enable fenceless farming. There are other forms of livestock farming systems that don't use fences. Currently fences fulfil the role to contain livestock, however we consider the opportunities for on-animal devices that can monitor and control livestock movement. These opportunities are extended to consider not just livestock management but also the opportunity to better connect the food supply chain. On-animal fenceless monitoring systems could re-imagine the relationship between food supplier and food consumer and create a new metaphor of open free access. Currently there are a number of research and development activities focussed on delivering automated animal control that have the potential to create fenceless farms. The first section of the paper reviews the role and scope of fences and the realistic potential to remove or replace them. It then explores the fence as a metaphor of disconnect between food producers and food consumers. This metaphor does not reflect the physical divide of farms but relates to the information divide and how fenceless farming technology can be used to monitor and share information. The paper considers why we might need to think about change, how that change might occur and what it might mean for the livestock, the farmers and the broader community throughout the supply chain. In looking to the future, the paper aims to present possible future scenarios, in so doing the authors acknowledge that this paper presents a limited set of options. The conclusion considers how the example of fenceless farming might have lessons for the future direction of farming and food supplies.

THE ROLE OF THE FENCE FOR LIVESTOCK PRODUCTION

The fence for livestock farming represents the ability to contain and manage domesticated livestock. There are a number of features of animal control systems that extend the notion of boundaries, and the descriptions represent varying functional features. We typically might envision controlling livestock with posts in the ground, wire hanging between them and a gate in one corner, while this is the most common form of control it is certainly not the only form. Livestock control can be represented by the variation in density or numbers of animals being contained, the form of the boundary and how permanent the boundary system is.

Containment in the broadest sense enables more efficient animal management. Extreme extensive livestock production systems that are typical of arid rangelands, such as those found in northern Australia, have highly variable seasonal forage growth. Studies in northern Australia provide an example of the importance of flexible stock management to avoid over or under grazing (Ash and Smith, 1996; Bortolussi et al., 2005; Hunt, 2008; Cullen et al., 2016; Pahl et al., 2016). Fencing these large and extensive areas is expensive and time consuming. The role of the fence in these extensive areas is to manage the feed-base, in particular to ensure there are grazing resources to carry cattle through extended dry seasons (Cullen et al., 2016). Fenced areas also provide easier access to cattle at key times in the production cycle. For example, drafting or separating cattle for sale or weaning calves from cows. There is an implicit connexion between the role of the fence and labour efficiency (Lomax et al., 2019). The extensive nature of the production environment in extensive rangelands makes it very difficult to locate and gather cattle and the fence provides an important role in trying to make this job more labour efficient.

The most intensive livestock production systems result in boundaries and fences that contain large numbers of individual animals in very small areas (Barry et al., 2015; Lomax et al., 2019). The most intensive production systems occur in fully contained housing where the livestock production results from fully controlled environmental conditions. Intensive housed production system optimises conditions to maximise food conversion efficiency as well as high levels of automation to optimise labour inputs (Astill et al., 2020; Martinelli et al., 2020).

The fence or boundary is considered a management tool to contain farm livestock. However, modern livestock agricultural systems sit within a broader supply chain and require external nutrient and energy inputs to sustain production. The lifecycle of livestock production includes movement between fenced areas both within a farm and between farms. Eventually the livestock enters the complexity of the human food chain.

In addition to enabling more efficient livestock production management a fence or boundary can be used to stop or reduce domesticated livestock damaging protected areas (Mysterud, 2010; Woodroffe et al., 2014; Jakes et al., 2018). These areas could have environmental value or have other uses that require livestock exclusion for example roads.

The fence is an example of a technology that has been used throughout modern agriculture to improve livestock management. The primary application of fences has been to restrict livestock movement. The ability to more easily manage larger groups of livestock has resulted in reductions in the number of people needed to manage livestock as a source of food for the broader population. A side effect of the fence has been for modern farming to be able to successfully keep the majority of people away from livestock production. In the context of Hardin's "Tragedy of the Commons" the fence removes the need for shared responsibility, the fence results in responsibility and consequences being assigned to "the owner."

THE FOUNDATIONS OF A SOCIAL CONTRACT TO DELIVER FOOD SECURITY—THE METAPHORICAL FENCE

The history of human food security from early hunter gatherers through to current farming systems is one of the trade-offs between time and energy or nutrients (Pimentel and Pimentel, 2007). Successful food security can be considered as a function of energy or nutrient supply per unit time. Technological innovation whether through improved hunting methods or improved farming systems is typically judged against the ability to deliver safe and healthy food security (Chávez-Dulanto et al., 2021). Measures of success for any given innovation might be efficiency of energy or nutrient supply. Key attributes of human food supply are founded on food sharing, labour exchange, and labour specialisation (Kramer and Ellison, 2010). The cooperative food model relies on individuals pooling food resources and this allows nutrients to be allocated to maintenance, production and a third pool of general activity (Kramer and Ellison, 2010). Cooperation in food supply leads to division of labour across a range of complex tasks, it supports specialisation especially when there are inequalities in the rates of return for specific activities. It also provides a foundation where time and effort allocation to acquire energy can vary between individuals within a cooperative group. This variation has particular value for humans that require long-term care of immature offspring (Charnov, 1991; Larke and Crews, 2006).

The cooperative food model results in innovation focussed on outcomes that maximises time allocation to general activity. In the context of nutrient or energy budgets the general activity is any activity that isn't directly related to an individuals own maintenance or reproductive effort i.e., activity that delivers to shared community value. Within the general activity allocation individuals can specialise in their contribution. The efficiency of food security creates opportunities for individuals to further specialise in activities that support the broader community goals. The progression and industrialisation of agricultural societies allows individuals to contribute to the community through the specialisation in the provision of livestock related nutrients. The adoption of fencing technology provides an example of an innovation that increases the labour efficiency of livestock rearing as well as the total productivity per person (Pimentel and Pimentel, 2007).

The pooling of resources, community cooperation and increased innovation through specialisation provides a foundation to deliver an increasing pool of nutrients and energy (Kramer and Ellison, 2010), in practical terms surplus energy and nutrients can be traded for time. The success of the pooled resource model relies on maintaining community co-operation, this becomes more challenging as the size of the community that is sharing the resource grows (Epstein et al., 2021). Specialisation results in a co-dependency that helps cement the cooperation. Community symbols that demonstrate the value of cooperative efforts can also help maintain the effort to pool resources as demonstrated in modern agricultural shared resource models (Cornée et al., 2020). There are examples of major human endeavours founded on a combination of innovations that deliver surplus nutrients freeing time to deliver symbols that demonstrate the power of pooled resources. It is estimated that the development of irrigation technologies coupled with fertile soils along the Nile in Egypt coincided with the building of the pyramids. Calculations have estimated that the surplus energy through efficiency and improved crop yields from the innovative irrigation practises was approximately equivalent to the energy required to build the pyramids (Cottrell, 1955). This energy was in the form of human labour that specialised in construction and was fed by the increased crops yields associated with irrigation innovation.

Livestock containment using fences, hedges and walls can be considered in the context of community driven energy and nutrient pooling and has been utilised to varying degrees throughout the development of modern agriculture. Increased division of activities through specialisation results in the fence as a symbol of the growing impact of the success of innovation. This success combined with other innovations has resulted in modern food supplies requiring a very small percentage of the population to deliver nutrients and energy to the broader community. Most community members have been completely excluded from delivering food security. Modern agriculture has liberated energy and nutrients that can be allocated to the broader community activities pool, but this success has resulted in a disconnect. Specialisation and innovation practises that support modern agricultural practise rely heavily on energy dense inputs such as fossil fuels in the form of agrochemicals, fertilisers and fuels for machinery. Disruptions to these energy dense farming practises creates a response that seeks to ensure the fundamental community need for food security is met. An example of a community response can be seen in the disruption to the Cuban food supply with the advent of the 1990's oil embargo. There was a shift from mechanised power to human power with more people directly involved growing food. Local community food supplies were prioritised over global food supplies with a shift away from commodity crops such as sugar and a shift towards crops that could be grown and consumed locally such as vegetables (USDA, 2008; Leitgeb et al., 2016).

As increasing numbers of people become more disconnected from growing food, they lose knowledge and understanding of the practical constraints to maintaining food supplies (Donald and Blay-Palmer, 2004; Sandover, 2020). This disconnect is further compounded with increased food processing that masks the origins of a particular food. Our biology demands that as individuals we need to secure a regular supply of food to ensure we have sufficient energy and nutrients. Within Maslow's hierarchy of needs food is considered as a base physiological need (Maslow, 1943). These base physiological motivations are important drivers of human behaviour. More recently researchers have been exploring a hierarchy of food needs (Satter, 2007). This hierarchy starts with meeting a basic need of having enough food. As food supplies become more abundant, we satisfy a goal for reliable ongoing access to food and our motivation moves towards greater food. Choices are initially driven by taste reflected in a desire to access novel foods. The highest motivation is a need for instrumental food that achieves a physical, cognitive or spiritual outcome and may or may not be supported by scientific evidence. This hierarchy of needs is where foods derive value beyond the nutrients they supply.

In designing future farming landscapes, the historical, physical, social, cultural, and psychological drivers of our individual responses to food security can be easily ignored. As we consider emerging agricultural innovations and how they might shape future farming landscapes we might consider the broader motivations that shape a community contract to access food and that have a strong foundation in the cooperative food model (Kramer and Ellison, 2010). Expanding the technological opportunities for fenceless livestock production to deliver value beyond the farm gate might be important for reconnecting farmers with the broader community. While the fence is not responsible for keeping people away from farms, however, in industrialised farming labour efficiency has resulted in consumers having less contact with food production. The technology driving fenceless farming provides an opportunity to provide consumers with virtual information and insight into livestock production methods. Finding ways to strengthen connexions might help shape understanding of the opportunities and constraints that modern agriculture faces.

TECHNOLOGY DEVELOPMENTS REQUIRED TO DELIVER FENCELESS LIVESTOCK FARMING

Removing the need for fences will require alternative methods that can be used to monitor and manage livestock. Current fencing provides a range of management benefits including controlling access to feed resources, delineation of livestock ownership, and to provide easier access to animals for routine management such as daily milking of cows. In addition to management requirements there are also a range of different production environments reflected in factors such as total farm or paddock size, numbers of animals contained in a paddock or across a farm (stocking rate) and the natural topographic and environmental features that form the basis for the livestock containment. Finally adjacent properties will be governed by different managers that have different goals. In some cases, these goals might require certain areas to not have access to livestock. These broad drivers define the role of the fence and need to be translated into technological solutions for fenceless farming systems (Barry et al., 2015; Jakes et al., 2018). Broadly speaking the fence characteristics can be defined by a combination of a permanency and permeability factor. Permanency defines the temporal requirement to contain livestock. Permeability defines the spatial requirements to contain livestock and determines how leaky the fence can be.

Fenceless technology that can be used to manage the movement of free ranging livestock will need to monitor, stop, and move animals without the need for a physical barrier. There are a range of technologies that are under various stages of research and development. Underpinning the spatial framework is access to digital maps and global positioning systems (GPS). It is now possible to use a GPS device combined with a digital map to identify the exact location and reference this location in regard to underlying resources e.g., the property you are located in and the exact location within the property. The development and application of these technologies for livestock systems warrants a paper in its own right. For the purposes of this paper, we accept there are challenges but the principles of remote and automated location and relative location are considered to be broadly solved but require some specific refinements mainly in power management related to location frequency and form factor related to the device being fitted and remaining in place and working on free ranging livestock (Swain et al., 2011). In general terms the technology framework for remote automated management of livestock falls under four broad categories. Off animal monitoring (Menzies et al., 2017a), off animal control, on animal monitoring (Swain et al., 2011), and on animal control or virtual fencing (Anderson, 2007; Bishop-Hurley et al., 2007; Umstatter, 2011; Umstatter et al., 2013; Anderson et al., 2014; Muminov et al., 2016; Lomax et al., 2019). Broadly speaking these technologies rely on manipulating behaviour through a combination of managing critical resources that livestock require on a regular basis e.g., watering points and directly controlling livestock behaviour through cues and controls. Livestock need to access certain resources on a regular basis (e.g., water), it is possible to control access to these resources and restrict when and how animals can gain access. An example of technologies that control resources to manage livestock is walk-over-weighing where livestock have a simple electronic identification tag that is read as the animals walk over a set of weigh scales. Their weight, ID, data and time and frequency of visits can be recorded. These data can be used to infer a range of production metrics such as growth rate, date of birth, oestrus detection and maternal parentage (Menzies et al., 2017a; Corbet et al., 2018; Imaz et al., 2020). The system can also have a drafting or control gate fitted, this allows the animals to be remotely and automatically drafted from the main group. On-animal monitoring requires livestock to be fitted with smart technology that can monitor the animals changing state. These changes include body movement, changing location and physiological parameters such as temperature or heart rate (Kour et al., 2018; Edwards et al., 2020; Högberg et al., 2020; Islam et al., 2020). The sensor devices log the data locally and then transfer it via a range of different communication technologies. Unlike the off-animal monitoring system that only requires electronic identification which has relatively small amounts of data (a few bytes) and can use radio frequency to power the tag, the on-animal monitoring technologies require a power source, local data storage, higher bandwidth communication, and potentially on board processing. The final stage of on-animal control uses animal sensors to provide real time monitoring that use location and behavioural sensing to track movement and then use this information to administer an aversive stimulus when the animal is required to stop or change direction (Anderson, 2007). The move from the simplest technologies that use off animal monitoring to the most complex on animal control sees increasing technical challenges and complexity of solutions. This complexity is reflected in the commercial readiness of the various stages of technical solutions, with off animal technologies already starting to be used by industry but on animal technologies are still in the development phase.

Individual animal management optimises fenceless farming systems. In most cases this optimisation utilises some form of electronic identification. In Australia the National Livestock Identification System (NLIS) was introduced to provide cattle producers with an electronic identification tag that utilised radio frequency identification (RFID) (Trevarthen, 2007; Iglesias and East, 2015). The NLIS has compliance requirements that all animals leaving a property have to have an electronic tag and that movement between properties was tracked via a central NLIS database. The imposition of RFID technology has created opportunities for software and hardware developers to deliver technologies that help with on-farm management (Trevarthen and Michael, 2008). For example, automatically reading cattle tags during routine cheques in the yards. The RFID technology is also a key component of walk-over-weighing technology. Electronic identification is not mandatory in all countries and there are additional costs for tags and readers. In remote locations there are challenges in identifying newborn animals that don't have ear tags. There has been initial development work on building vision recognition software that can identify individual animals for example sheep (Noor et al., 2020). Remote and automated vision recognition software could address the challenges of tracking individual animals. Some systems can also be used to track group performance and manage overall changes in the state of the herd.

The broader framework for delivering fenceless farming systems will be increasingly enabled by technical developments in what has been termed the "internet of things" or IoT (Astill et al., 2020; Ilyas and Ahmad, 2020; Prabowo et al., 2020). This framework is built on distributed sensors that connect through a hierarchy of communication layers with feedback, data processing and data integration. The hierarchy has three core layers: the node (the animal), an intermediary in field integration system (edge computing) and a centralised computing system (the cloud). The taxonomy and functional features required by the IoT to support fenceless farming systems has been overlooked. In line with a broader agenda driving a third industrial revolution the IoT framework creates opportunities for greater democratisation, broader participation, greater trust and a higher degree of automation. Integral to the success of the IoT is the extent to which it leverages applications based on algorithms, enhanced automation and greater trust through authenticated and encrypted data. The distributed nature of the problem and the opportunity to engage multiple stakeholders can add value across farming systems and built around small scale connected and shared services, IT developers typically refer to these as micro-services (Maia et al., 2020). The foundation for these services requires an interconnected IoT framework that is divided not by stakeholder ownership but by what each service delivers (Devi et al., 2019; Santana et al., 2021). The success of these systems requires an outward looking model, where developers and stakeholders aim to deliver value to clients through cooperative services (Iqbal and Butt, 2020). The use of application program interfaces (APIs) embedded across sensors, edge and cloud computing will enable a shared set of services

(Santana et al., 2021). In many cases remote locations that have poor connectivity will require innovative methods that ensure event-based services are delivered when data flows are interrupted and asynchronous (Devi et al., 2019). This is an area of development that needs much greater work in the context of remote systems that are typical of the backbone of livestock farming systems.

The rapid development of sensor-based technologies for livestock applications promises to deliver the potential for fenceless farming systems sometime in the next 10 years. In particular it is likely that practical applications of the technologies will result from using a range of technologies that complement each other and deliver increased efficacy and accuracy that is practical, sustainable, and meets consumer welfare expectations. This combination of technologies will manage livestock movement using a carrot and stick approach, where access to water and supplementary feed can be used as an attractant and virtual fencing can be used to restrict access across the landscape. It is yet to be seen whether it will be possible to remove all fences, however, even if internal property paddock fences are no longer required it is likely that livestock producers will still require cattle yards with fences which can be used for routine management such as administering animal health or preparing livestock to be sold. Event based microservices that are supported by the IoT are emerging as a potential framework to deliver enhanced value for fenceless farming systems. This technology will deliver broader benefits of fenceless farming technology and provide a framework to connect new value through the supply chain. Integral to the microservices framework is an intrinsic focus on enabling value through shared services and this feature has the potential to extend and potentially outweigh the value of fenceless technology beyond just controlling livestock. The next sections explore the direct and indirect opportunities and benefits of fenceless livestock farming technology.

THE APPLICATION OF FENCELESS FARMING—DEFINING A NEW PARADIGM

As previously stated, the fence is one of the oldest agricultural innovations and synonymous with livestock farming. The fence divides the landscape into discrete self-contained geographical units (farms, properties, paddocks, or fields) that are allocated to discrete groups of livestock at certain times of the year. Ownership or control of land and animals are tightly coupled, and this coupling addresses the potential for a "Tragedy of the Commons" by maintaining a productive landscape through managers that consider both the landscape and the animal and maintain a balance between them both (Hardin, 1968). Movement of livestock between properties usually coincided with the transfer of ownership. The fixed nature of a fence creates permanency and instils trust but also doesn't allow opportunities for more flexible and refined management options that might reflect a common approach (Cornée et al., 2020). Flexible and refined management options can be defined by the ability of the system to monitor, reconfigure and deliver customised individual animal grazing management.

Shared grazing commons form part of existing livestock production systems. How will on-animal technologies deliver new opportunities for shared grazing resources? Sensor based technologies provide continuous monitoring and feedback to allow more refined control of how grazing animals can access shared resources. The system also allows greater shared insight to all users of the shared grazing resource on how each individual animal is accessing the grazing resources. Automated monitoring and control can increase labour efficiency. It is not clear whether these are desirable characteristics, but they are points of difference for technology driven fenceless farming.

Integrated sensor-based systems have the potential to underpin the livestock management decision framework with regular updates on the state of each animal (Ilyas and Ahmad, 2020). The combination of on animal sensors coupled with edge computing modules that can add further data will provide the foundation for the customised individual animal management decision. Practical constraints for animal sensors such as power management and communication will require the edge computing capability to provide a layer of support in coordinating the individual animal monitoring (Alonso et al., 2019; Yang et al., 2020; Bergier et al., 2021). The monitoring systems will have embedded algorithms that can track a range of factors and use movement linked to behaviour as proxies for physiological state (Williams et al., 2017, 2020; Fogarty et al., 2020a,b). Examples of animal state information that will drive decision making would include health status, productivity including growth rates and reproductive status and welfare status (O'Neill et al., 2014; Swain et al., 2015; Menzies et al., 2017a,b; Corbet et al., 2018; Kour et al., 2018, 2021; Fogarty et al., 2020a,b). Animal location information can be used to determine livestock movement and livestock landscape preferences (Swain et al., 2011). Integrated micro-services will use baseline generic algorithms but these will be refined within the system to take account of individual animal parameters (Devi et al., 2019; Taneja et al., 2019; Maia et al., 2020; Santana et al., 2021). In addition to livestock monitoring external data will be added to the system to provide a further context for management decisions. These data could include remote sensing data for local grazing information, information on the broader feed resource options e.g., understanding the potential impact of a drought, individual market options, genetic improvement opportunities and general information that could impact any final decision e.g., the potential effect of a political decision, such as a trade deal, on supply chains (Swain et al., 2011). Critical to the foundation of the application of the fenceless management system is the integration of sensor data drawn from the animals through the edge computing and including cloud computing (Alonso et al., 2019; Yang et al., 2020; Santana et al., 2021).

The removal of fences across privately owned land creates a system that more closely resembles "the commons" as it provides the opportunity for cattle to move between private land parcels and access what can become a shared grazing resource. There are now no longer any boundaries between paddocks or properties. Using the example of cattle then producers still own their livestock and land but it is possible for a cattle owner to easily exploit their neighbours grazing resource. Given Hardin (1968) has already alerted us to the problem of selfish motives undermining sustainable resource use then fenceless farming technology could be doomed to failure. Unlike the traditional commons which rely on grazing managers being trusted the fenceless farming system has oversight underpinned by sensor technology that can be used to validate grazing managers claims.

Fenceless farming could be built on current farming operations and livestock management practises albeit with more refined control; the managers only access the land and grazing resources they control. While there are certainly potential cost saving and production benefits from this approach it misses the opportunity to adopt a more holistic management framework. Before fences were introduced grazing herbivores would form herds that moved across the landscape according to feed availability, these herds involved complex behavioural interactions (García et al., 2020). In natural unfenced grazing systems supply and demand ensured a natural balance was formed between forage availability and herbivore numbers, managed grazing systems integrate management technologies such as fences (Bailey et al., 2019). Virtual fencing technologies create an opportunity for fenceless farming systems to decouple livestock from land units. Farmers will own land or feed resources and cattle, but they may not always exist in the same location. The ability for livestock to move more freely and access available feed wherever it occurs capitalises on the removal of fences. The sensor systems could monitor the natural cattle preferences and subtly orchestrate broad scale movement. Restricted access to water could be used by owners to implement individual animal intervention strategies. The spatial movement of livestock could be linked to payments for landowners to receive payments from cattle owners for access to feed. The independent integrated and validated sensor-based systems would form the basis of pre-arranged contracts that ensured transparency and equity.

Commercialisation of virtual fencing technology is underway; however, widespread adoption has still not occurred. The technical challenge of powering and maintaining on-animal monitoring and control devices is significant. It is likely that early commercial applications will occur in more intensive livestock production systems such as dairy. These systems are more capital intensive to offset the costs of the equipment and they also allow more routine access to the cattle to upgrade or maintain the technologies. The long-term value proposition for these technologies will require the systems to derive multiple benefits for example providing feedback on animal health and welfare as well as containing the cattle.

RENEWING A SOCIAL CONTRACT—FENCELESS FARMING PUTTING COMMUNITY AT THE HEART OF FOOD SECURITY

In earlier sections, we explored how studies have shown the foundations of human food security is based on a model that supports an implicit social contract resulting in energy and nutrients being made available for activities that enable individual specialisation (Kramer and Ellison, 2010). The foundations for human specialisation have resulted in modern agriculture based on a cooperative model and relies on maintaining a social contract. The success of the agricultural model has been in labour use efficiency, that is the energy output per unit of time directly involved in supplying food (Pimentel and Pimentel, 2007). While total global food production has increased this has been largely as a result of energy intensive farming practises on the back of the introduction of fossil fuels. Overall energy efficiency [energy harvested per unit of energy input (not including solar energy)] has not significantly changed (Pimentel and Pimentel, 2007). The labour use efficiency for modern food production means that large proportions of the population no longer need to be directly involved in food production. Food is an essential foundation for our very existence. However, we also demonstrated that our relationship with food changes as food becomes more abundant. As basic food needs are met there is an increasing desire for foods to represent core values (Satter, 2007). These values can be related to how the food is grown, nutrient properties or taste. The food supply chain increasingly provides information that helps to connect the food grower with the food supplier.

As stated earlier the application of fenceless farming systems will require sensor technologies that can continuously monitor the state of the animal. These sensors will also be able to deliver a range of micro-services via communication infrastructure that can be used to manage the complexity of the system (Taneja et al., 2019; Maia et al., 2020). These services will be built on insight related to animal health and welfare, genetics and environmental (including but not limited to the feed-base) drivers. Micro-services will deliver technological insight through algorithms, efficiency through automation and trust through authenticated encrypted data streams. The underlying connectivity and availability of information will drive opportunities to create greater democratised responses to consumer needs and wants (Davies and Garrett, 2018; Suhail et al., 2020).

The driver for previous agricultural innovations has been labour efficiency increased output per unit labour input (Pimentel and Pimentel, 2007). Reducing labour reduces costs and the technologies driving this innovation have facilitated an industrialised approach to agricultural production. Homogenisation of technologies such as genetics refines the production methods. However, complex supply chains can make it difficult for farmers to connect with consumers and create value by delivering specialised products that consumers are willing to pay more for (Clark et al., 2020). Critical to raising the value of a product is the ability to differentiate it in the marketplace (Schulze-Ehlers and Anders, 2018). Product differentiation needs to connect the supply chain and create unique selling points that consumers understand and are willing to pay for (Polkinghorne et al., 2008). The technology that will sit behind fenceless farming systems provides an opportunity to have detailed monitoring of the production systems. When there is an abundant supply of food that is not price sensitive then consumers become more interested in food that reflects their environmental values, so they are willing to be more selective in purchasing food (Canavari and Coderoni, 2020). The sensor system embedded in virtual fencing can be combined with independent authenticated and encrypted information and used to demonstrate the efficacy of the food production systems (Mondal et al., 2019). Traceability is not dependent on virtual fencing, but it provides added value to this emerging technology. It is theoretically possible to be able to trace individual animals through the supply chain so that a final product can tell a storey not of a region or a farm or even a group of animals but can provide detailed information on an individual animal.

The ability to build a more meaningful and trusted social contract delivering not just food but information about that food can build value in the supply chain (Gale et al., 2017; Sharma et al., 2020; Zhang et al., 2020). Reconnecting community members that are no longer directly connected to growing food will help to build a greater awareness of the realities of managing farms that supply food (DesRivières et al., 2017; Raatikainen et al., 2020). The ultimate democratisation of food production might occur when we start to see a shift back to a greater percentage of the population having direct involvement in food production (Ikerd, 2019; Ochoa et al., 2020). The ability to track livestock assets has the potential to extend the idea of remote livestock ownership. Livestock producers could become landowners and get paid to manage livestock when they are within the geography of their property. As livestock owners the broader community will face the costs and benefits of raising animals. Consumers will be able to directly pay to take land out of livestock production and create conservation areas.

Technological innovation will provide the foundation to allow livestock management without fences (Anderson, 2007). That same technological innovation can also re-frame the relationship between farmers and consumers. Removing the metaphorical fence is to throw into question the social contract, the business and ownership of both livestock and land. When food is in short supply or technological innovation is disrupted, such as happened with Cuba during the oil embargo, then communities look to directly connect with growing food (Cederlöf, 2016). When food is in abundant supply then there is little need to directly connect with growing food. However, if fenceless farming provides a framework for communities to directly connect and shape food production to meet their values then it has the potential to build greater understanding between farmers and consumers. Not only will this help ensure profitable and sustainable food production, but it will also build a community that is more directly connected to growing food. The knowledge and understanding might be important if growing food needs to revert back to a more human centric activity.

CONCLUSIONS

Containing livestock using fences is an integral part of modern agriculture. The origin of fences provided an early foundation in the move from hunter gatherer communities to settled agrarian societies. While the practical animal management benefits are obvious, the impact of the fence in assigning property rights and the cultural impacts are more complex and potentially far reaching. The fence not only contains livestock but can also exclude access. Using a fence as a tool that divides the landscape and in so doing creates ownership has the potential to assign responsibility for societies expectations in regard to meeting welfare and environmental standards. In theory this approach should address the "Tragedy of the Commons" albeit through shared values rather than shared land (Hardin, 1968). The emerging opportunity for fenceless farming systems is founded on the premise of delivering more cost effective, flexible and refined management options for free ranging livestock. This goal addresses the containment issue. It is possible that the underpinning technology could address a far more important issue that reflects a greater connection between food producers and food consumers, enabling a value based social contract built on producers being able to realise greater market value.

There is growing evidence in the literature that the technical goal to contain and manage livestock using fenceless systems, referred to as virtual fencing, is making good progress. The implementation of virtual fencing as a management tool will need to match technology with practical and economic considerations before wide scale removal of traditional fencing can occur. There is currently little evidence to indicate what the economic or practical costs and benefits will be for virtual fencing. New innovative technology solutions like virtual fencing have the potential to create new and unimagined value. This value sometimes requires the technology to be extended and reframed. The opportunity for fenceless farms to reconnect consumers with producers could create opportunities for producers to drive new unrealised market value. This value will be based on trusted information that addresses broader societal values. To achieve this new value will require virtual fencing technology to become embedded within a broader information framework. Currently this broader outward focussed micro-service technology solution is missing from the more inward monolithic technology solution that is driving fenceless farming solutions such as virtual fencing.

Fenceless farming systems for livestock production provides the opportunity to explore how emerging technology might reshape and reconnect people's relationship with food. In general, the rise in digital technologies has impacted agricultural production systems. The IoT coupled with automation and algorithms is allowing tools such as machine learning to deliver refined and optimised solutions. Evolutionary trajectories show us that nature has been very good at tweaking phenotypes to find the best fit and this approach leads to diversity with local optimisation. The digital framework and IoT is yielding greater volumes of data that are delivering more refined local insight. Like evolution this insight creates opportunities for diversity and local optimisation. This opportunity should result in food production that moves away from homogenised gene pools, production systems will be based on local opportunities reflected in greater connexions between consumers and producers. Fenceless farming systems might put a new spin on the problem of the "Tragedy of the Commons," using data to confirm shared values and technology to deliver shared responsibilities.

AUTHOR CONTRIBUTIONS

The ideas for this paper and the writing of the manuscript came predominantly from DS. SC helped shape the ideas and reviewed the manuscript. All authors contributed to the article and approved the submitted version.

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frontiers in Sustainable Food Systems

REVIEW
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Using Research to Support Transformative Impacts on Complex, "Wicked Problems" With Pastoral Peoples in Rangelands

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Pastoralists and researchers (and others) are finding new ways of working together worldwide, attempting to sustain pastoral livelihoods and rangelands in the face of rapid and profound changes driven by globalization, growing consumption, land-use change, and climate change. They are doing this partly because of a greater need to address increasing complex or "wicked" problems, but also because local pastoral voices (and sometimes science) still have little impact on decision-making in the governmental and private sectors. We describe here, using six worldwide cases, how collaborative rangelands partnerships are transforming how we learn about rangelands and pastoralists, whose knowledge gets considered, how science can support societal action, and even our fundamental model of how science gets done. Over the long-term, collaborative partnerships are transforming social-ecological systems by implementing processes like building collaborative relationships, co-production/co-generation of knowledge, integration of knowledges, social learning, capacity building, networking and implementing action. These processes are changing mental models and paradigms, creating strong and effective leaders, changing power relations, providing more robust understanding of rangeland systems, reducing polarization and supporting the implementation of new practices and policies. Collaborative partnerships have recurring challenges and much work is yet to be done. These challenges rest on the enduring complexity of social-ecological problems in rangelands. At a practical level, partnerships struggle with listening, amplifying and partnering with diverse (and sometimes marginalized) voices, the time commitment needed to make partnerships work, the bias and naivete of scientists, the recognition that partnerships can promote negative transformations, management of power relations within the partnership, and the need to attribute impacts to partnership activities. We think that the future of this work will have more focus on systems transformations, morals and ethics, intangible and long-term impacts, critical self-assessment, paradigm shifts and mental models, and power. Overall, we conclude that these partnerships are transformative in unexpected and sometimes intangible ways. Key transformations include changing mental models and building the next generation of transformative leaders. Just as important is serendipity, where participants in partnerships take advantage of new windows of opportunity to change policy or create new governance institutions. We also conclude that collaborative partnerships are changing how we do science, creating new and transformative ways that science and society interact that could be called "transformative science with society."

Keywords: transformations, social-ecological systems, social learning, pastoralist, collaborative partnerships, co-generation of knowledge

INTRODUCTION

A recent global assessment (IPBES, 2019) led to the logical conclusion that achievement of global equity and sustainability requires rapid change. It is not enough to make incremental, adaptive change; rather, we need transformational change with rapid leaps to a new normal (O'Brien, 2012; Moore et al., 2014; DĨaz et al., 2019). Here, a "transformation" is a change process that creates a fundamental change in the purpose, structure, form or function of our social, economic or ecological systems (Walker et al., 2004; Moser, 2016).

These transformations can be deliberate or unintended (O'Brien, 2012), initiated by governments, civil society, the private sector, citizens or others. They can also be driven by natural disasters, abrupt climate change or other system changes. Deliberate transformations occur because the existing system is no longer tenable (Walker et al., 2004). This may mean transforming how we lead, how we learn, the way our institutions work, and how we think about nature and society (Pennington et al., 2013; Abson et al., 2017). It also means creating innovative, adaptive, inclusive, just and equitable governance approaches (DĨaz et al., 2019); promoting the use of social innovations and social entrepreneurs (Westley et al., 2006, 2017; Biggs et al., 2010); strongly respecting and combining different knowledges (Agrawal, 1995; Berkes, 1999; Max-Neef, 2005; Tengo et al., 2014; Mistry and Berardi, 2016); and integrating across systems, jurisdictions and tools (DĨaz et al., 2019). Scholarship on transformation has typically focused on understanding the external process of transformation (Olsson et al., 2006), rather than the mechanisms that lead to internal changes, which have been proposed to be more durable and impactful (Meadows, 1999; Abson et al., 2017).

When scholars and practitioners describe rangelands, they describe multiple transformations, both deliberate and unintended. A common deliberate transformation is a change in land tenure from the pastoral commons to either public conservation land (like parks) or to private land (Galvin, 2009; Herrick et al., 2012; Reid et al., 2014a). Transformations also consist of changes in land use from pastoralism to extractive industries, cropland, and exurban development or shifts from family-run ranches to ranches run by absentee owners (Fernández-Giménez, 1999a; Gosnell et al., 2006). Or they involve the shift from state-owned livestock to privately owned livestock with the fall of communism in central Asia while, in some instances, expanding unsustainable herd sizes (e.g., Fernández-Giménez, 1999b; Kerven, 2003). Clearly transformations can be either positive or negative depending on your values and worldview. Rangeland scientists often study these transformations in state-and-transition models, which describe how the linked social-ecological system can shift from one state to another through transition processes (Briske et al., 2005). Unintended transformations include the loss of grassland productivity due to climate change (e.g., Bruegger et al., 2014) and shifts in pastoralism caused by drought and winter storms (e.g., Fernández-Giménez et al., 2015).

Another deliberate transformation, aimed at positive transformations from a pastoral worldview, are those driven by rangelands partnerships. Diverse and collaborative partnerships involve participants with different values, incentives, priorities and knowledges, like Indigenous peoples, ranchers, pastoralists, government managers, conservation practitioners and researchers. Partnerships form to achieve a particular goal (O'Brien, 2012) within a particular grazing social-ecological system. Rangeland partnerships learn together and forge new solutions to problems they identify for particular places. In the process, they transform the participants, reducing polarization and creating "face-to-face" democracy (Brick et al., 2001; Conley and Moote, 2001; Knight and White, 2009; Knight, 2010). For example, the Blackfoot Challenge and the Malpai Borderlands are two rancher-led partnerships in the US that formed to prevent further fragmentation of open, rural landscapes and to address the loss of biodiversity caused by woody plant encroachment on grasslands (McDonald, 2002; Charnley et al., 2014; Wilson et al., 2017; Belsky and Barton, 2018). These alliances have been called "strange bedfellows" or "unlikely," alluding to partnerships of diverse participants who have historically been at odds, like ranchers and environmentalists (Hillis et al., 2020). In Africa and Asia, these are often called community-based natural resource (or rangeland) management initiatives (Dressler et al., 2010; Shackleton et al., 2010) or, more broadly, community conservation initiatives. These community-based partnerships are important because rural communities and Indigenous Peoples use and manage over half of the Earth's land collectively under community-based, customary ownership systems (Alden Wiley, 2011).

Some of these collaborative partnerships not only attempt to transform pastoral systems in a positive manner, but they also aim to transform how scientists work with pastoral peoples. They attempt to create science that meets the needs of pastoral peoples and the rangelands they depend upon. These diverse, problem-solving partnerships span the boundaries between science/research and practice/action (Lang et al., 2012). Scientists often play diverse roles like the reflective scientist, intermediary and facilitator in these joint learning processes (Pohl et al., 2010). Both in rangelands and elsewhere, these partnerships have created outputs, outcomes and impacts including useful products, relevant knowledge, increased decision-making capacity, deeper or wider networks, and transformational changes like economic benefits, decisions made and new organizations or policies established (Walter et al., 2007; Wiek et al., 2014).

This transformation in the way social-ecological science is done through collaborative partnerships is nested within a much broader change in science. In the last few decades, the part of science that focuses on societal problems has been quietly transforming into a whole new science (Klein, 2009; Knapp et al., 2019) in two principal ways (Hadorn et al., 2006; Lang et al., 2012; Cornell et al., 2013). First, scientists increasingly seek to understand complex (often called "wicked") problems using knowledge from several disparate disciplines. Most scientists are still trained in a single discipline and thus integrating two or more disciplines into interdisciplinary science (like ecology and anthropology) is rare and difficult to do well (Klein, 2009). Second, if scientists want their understanding of wicked problems to support broader society to solve those problems, scientists often have to work directly and collaboratively with other members of society, to co-generate knowledge, learn together and then experiment with implementing that new knowledge in on-the-ground action (called transdisciplinary science or science with society). We propose here that transdisciplinary science is evolving into a new science which focuses more on epistemologies (different ways of knowing, not just different knowledges), power, action and transformation of systems.

These collaborative partnerships of science with society are addressing another age-old problem: science is often not used by decision makers when addressing large scale and complex societal issues (Meffe et al., 2006; van Kerkhoff and Lebel, 2006; McNie, 2007; Reyers et al., 2010; O'Brien, 2013; van Kerkhoff, 2014). This "science-action gap" still exists even in areas of science that explicitly focus on applied societal problems like land degradation, biodiversity loss, climate change, food security, conservation, pandemic disease, and poverty. This gap exists because of high problem complexity, compartmentalization of knowledge and poor (or limited) collaboration between decision makers and scientists (Max-Neef, 2005; Hadorn et al., 2006). We think it also exists because decisions are ultimately made to benefit people who hold power and not all scientific results provide those benefits.

This evolution in science through partnership with society has a long history of thought and practice within the social sciences, medicine, health and, more recently, the biophysical sciences (Miller and Wyborn, 2018; Knapp et al., 2019). In different disciplines, this approach has diverse names with diverse definitions, including applied research, research with action, knowledge with action, science with society, transdisciplinary research with action, transdisciplinary research or science, public participation in science, translational science, Indigenous knowledge and science, collaborative adaptive management, sustainability science, civic science, post-normal science or Mode-2 research (Seidl et al., 2013; Knapp et al., 2019; Wyborn et al., 2019).

Today, these partnerships flourish in many ecosystems and work on a wide diversity of problems with some led by scientists and others by actors/practitioners (Chambers et al., in review). They often struggle to put science and action goals on equal footing (Reid et al., 2016a), to balance power dynamics among different participants (Schuttenberg and Guth, 2015; Miller and Wyborn, 2018; Knapp et al., 2019) and to adapt to changing issue dynamics over time (Mauser et al., 2013). A global analysis of 32 partnerships, primarily led by researchers, showed they had a wide variety of intended and achieved outcomes including knowledge production, knowledge transfer, capacity building, building networks, process learning, process quality, reframing the problem, empowerment, social equitability, institution building, policy uptake, management practices, and ecological and social outcomes (Chambers et al., in review).

Here we focus on what we will call science with society (SWS) partnerships in rangelands. Grazing in rangelands by wildlife and livestock herded by pastoral peoples is the most widespread way that humans use land (Asner et al., 2004) partly because rangelands cover 25–40% of the Earth's land surface (Asner et al., 2004; Reid et al., 2014a). Rangelands are also particularly marginalized, ecologically, economically and politically (Sayre et al., 2013). Rangelands may be extensive but per hectare productivity is low and pastoral peoples are widely dispersed and far from centers of power (Reynolds et al., 2007; Cleaver, 2012; Sayre et al., 2013). Pastoralists most often live in common land and thus often have weak ownership and decision making power over their lands (Reid et al., 2014a). With sparse populations and weak tenure, pastoral peoples are more subject to competition with other land uses. Pastoral land is also sometimes subjected to "land grabbing" by governments for conservation areas or commercial uses, and by farmers for crop cultivation (Abbink, 2011; Borras and Franco, 2012).

We suspect that collaborative partnerships may be particularly innovative, needed and impactful in rangelands, embedded in pastoral society. Why? Pastoralists, like many rural peoples around the world, must innovate with what they have at hand (or bricolage), partly because markets and centers of power are often far away. Thus research, if driven by pastoral needs, becomes part of that bricolage. Also, since pastoralists are marginalized and often have weak land tenure, they may engage in partnerships as a way to strengthen their voices with powerful government and private sector actors through the power of science and expertise.

On the research side in these partnerships, two patterns are evident. In our experience, pastoral scholars are strongly devoted to pastoralism and thus have the stamina and persistence to be part of these time-consuming partnerships. And, while this inclusive partnership approach is unfolding across the globe in many systems, it is especially needed in rangeland systems. Rangeland systems often support marginalized communities, thus SWS partnerships can be designed to highlight pastoral voices. Pastoralists and ranchers face similar challenges around the globe (Reid et al., 2014a; Espeland et al., 2020) and thus significant learning across sites is possible. Rangelands also are understudied; publications in the last few decades including the keyword, "rangelands," are about 2–3% of the number of publications that included the keywords, "farm," "forest," "marine," or "urban"[1]. More research, particularly aimed at information that local stakeholders need, could help fill this gap.

Here, we will briefly summarize our evolving science and SWS partnerships in rangeland systems. We will focus on if and how these partnerships support transformative action toward more sustainable rangeland systems. In this paper, we have three objectives:

1. To describe a set of cases of partnerships representing a diversity of approaches to developing and implementing integrated teams of pastoralists/ranchers and researchers, which are addressing critical issues in social-ecological rangeland systems.
2. To focus on the outcomes, impacts and impact pathways of these cases and then to assess whether these are and are not transformative, and if so, how.
3. To look into the future to the next evolution of science with society.

We will start by describing our case development methods, the six cases and a comparative case framework. We will then use our cases to exemplify key definitions, concepts and processes involved in these partnerships.

CASE DEVELOPMENT METHODS

The cases below were developed by the senior author based on literature, written and oral interviews and emails with the co-authors of this paper. The cases were not designed to be comparable with a common model and thus we base this analysis on logic and synthesis. The literature and other documents, interview transcripts, notes and emails were used to create a matrix of characteristics for the cases, with selected parts of that matrix summarized as **Table 1** (below). The lead author designed the matrix around top-level codes developed from the above information. The top-level codes arose partly from the literature and partly inductively from the cases and are the same across all the cases. Within those top-level codes are sub-codes (or lower level codes) in the cells in **Table 1** and these vary from case to case and thus form the basis for our case comparisons along with contrasting secondary data describing the cases from other documents. In the text, we use selected illustrative quotes to demonstrate key points. All authors read and approved the following descriptions of their partnerships.

OUR CASES AND THEIR CONTRASTING APPROACHES

Case Descriptions and the Theoretical Basis for Each Partnership Approach

CARM Project, Colorado (Wilmer Interview)

The Collaborative Adaptive Rangeland Management (CARM) project started in 2012 as a large, 10-year, ranch-scale participatory grazing experiment. A group of stakeholders and scientists co-created ways to manage the land in the semi-arid shortgrass steppe "to pass it on to future generations economically and ecologically." The partnership team consisted of "government agencies, conservation non-governmental organizations, ranchers, and interdisciplinary researchers" (Wilmer et al., 2018). The team's goal was to intensively experiment with contrasting grazing practices and then adapt as they learned. The problem of focus originated with the researchers but was of strong interest to the Crow Valley Livestock Cooperative, the local grazing association, as well. The partnership encountered disorienting dilemmas (see **Figure 2** below) in their intensive reflection and learning process and struggled with emergent complexities and trade-offs between grassland bird habitat and beef production (Fernández-Giménez et al., 2019b). They used processes like reflection, co-production/co- generation of knowledge and evaluation of outcomes that resulted in changing mental models and epistemologies, and social learning. Their intangible impacts include trust, understanding each other's perspectives, and ideas and management practices that are being used beyond the project (Porensky interview). Their best practices are deep reflection, experimentation and learning together (Wilmer et al., 2018; Fernández-Giménez et al., 2019b).

CARM was designed to test key hypotheses arising from an academic debate in the rangeland science and management community (Briske et al., 2011). The team was also responding to changing public demands for multiple ecosystem services on rangelands, and to a key gap in rangeland science: manager decision-making had been excluded from most grazing research in the USA for 8 decades. Several methodological and theoretical perspectives influenced project design. These were: (1) a tradition of customer-oriented, applied, and

[1]Our search of the Web of Science database on 30 June 2020 of the number of papers written in about the last 3 decades including the keywords of rangeland compared to papers using keywords of farm, forest, urban, marine.

TABLE 1 | Selected characteristics of six rangeland partnering case studies in North America, Europe, Africa, & Asia.

Characteristic	CARM project, Colorado, USA[a]	Samburu, Kenya[b]	Reto project, Maasailand, East Africa[c]	MOR2 project, Mongolia[d]	Spain[e]	Pamir Mtns, Afghanistan/Tajikistan[f]
Location of work	Experimental station, Colorado, USA	3 communities, Samburu, Kenya	5 ecosystems, 100 Maasai comm., Kenya (KN) & Tanzania (TZ)	36 counties, 11 provinces, Mongolia	4 sub-national regions, Spain	8 villages, Pamir Mtns, Afghanistan & Tajikistan
Project Scale (years)	Ranch level, 10 × 10 km (10 years)	County level, 150 × 225 km (6)	Int'l region, 400 × 650 km (15)	National, 800 × 1,200 km (8)	Regional, 400 × 400 km (3)	Int'l region, 250 × 250 km (13)
Goals	• Stakeholders co-develop goals and objectives • Manage land to pass it on to future generations • Collaboratively learn and adapt management based on monitoring data, stakeholder knowledge, and dialog	• Share pastoral knowledge & practice with NGOs & conservancies • Create co-learning opportunities • Drought planning sheep & goat husbandry	• Focus research on issues identified by community (breeds, vaccine, tourism profits, land use) • Assess synergies & trade-offs between pastoralism and conservation • Implement new science models to support communities & influence policy	• Co-design research to address priority pastoral issues • Assess CBRM social & ecological outcomes, and whether CBRM increases system resilience to climate and socio-economic changes • Build capacity of Mong. researchers to do TD science	• Co-create knowledge with women pastoralists • Document women's lived experiences as livestock keepers • Increase visibility of women pastoralists • Support pastoral women's networks to advance their agendas for social, economic and political change in the rural/livestock sectors	• Build trust • Co-generate knowledge • Create an outcome that is useful to communities to secure their livelihoods & food systems
Human development index[g]	Very high, 0.92	Med, 0.57	• Kenya = Med, 0.57 • Tanzania = Low, 0.53	High, 0.74	Very high, 0.89	Tajikistan = Med, 0.66, Afghanistan = Low, 0.50
Biome, rainfall mean or range	Temperate steppe, mean = 341 mm	Tropical savanna, 400–600 mm	Tropical savanna, 400–600 mm	Temperate steppe 130–400 mm	Medit. grasslands, woodlands & mountains, 250–1,800 mm	Temperate mountains
Dominant land tenure	Public & private land. Grazing on public land depends on owning private land	Public, private and community land	KN = Private, group ranch & public land. TZ = Village & public (trust) land	Public land used in common by pastoralists	Private, public, local commons	Public and private ownership
Stakeholder types	Govt, NGOs, ranchers, ID researchers	PhD student, pastoralists, comms	Govt, NGOs, pastoralists, ID researchers, comms	Govt, NGOs, pastoralists, ID researchers	NGOs, network, pastoralists, 3 ID researcher-activists	NGOs, pastoralists, ID researchers
Team size (# of disciplines)	Large (5)	Small (1)	Large (6)	Large (5)	Small (3)	Moderate (3)
Partnership process outputs	Collab relations, knowl int, co-prod, soc learn, network, implement action	Collab relations, knowl int, co-prod, soc learn, capacity	Collab relations, knowl int, co-prod, soc learn, capacity, implement action	Collab relations, knowl int, co-prod, soc learn, capacity, network	Collab relations, knowl int, co-prod, soc learn, network	Collab relations, knowl int, co-prod, soc learn, capacity, network
Partnership product outputs	Meetings, experiments, co-prod research, pubs, reflective evals	Meetings, co-prod research, feedback workshops, thesis	Meetings, co-prod research, outcome maps, pubs, tech transfer, new NGO	Meetings, co-prod research, reflective evals, pubs, feedback workshops, trainings	Meetings, co-interpreted research, feedback workshops, reports, pubs	Curriculum, co-interpreted research, conference, K-S platform, ML pubs
Outcomes & impacts	Social, biodiversity conservation, food production, drought resilience	Stronger leader, reframed gender, empowered voices	Social, econ, ecol, animal health, reframed narrative, leaders, policy	Social, team science process, leaders	Empowered voices, reframed gender, networks	Empowered voices, reframed narrative, education, policy, leaders
Best practices	Interaction intensity & experimentation	Multiple visits to design study	Community & policy facilitators	Team science, reflection, evaluation	Co-creation, linkage to activism	TD process, impact on policy

Govt, Government; NGO's, non-governmental organizations; ID, interdisciplinary; comm, community(ies); CBRM, Community-Based Rangeland Management; years, duration of main project; int'l, international; collab relations, collaborative relationships; knowl int, knowledge integration; co-prod, co-production/co-generation of knowledge or co-produced; pubs, publications; soc learning, social learning; capacity, capacity building; network, strengthening pastoral-research networks; pubs, publications; tech, technology; K-S, knowledge sharing; ML, multi-lingual; econ, economic; ecol, ecological; TD, transdisciplinary; Mong, Mongolian; Medit, Mediterranean ([a]Wilmer et al., 2018, 2019; Fernández-Giménez et al., 2019b; Wilmer interview, [b]Pickering interview, Apin interview; [c]Reid et al., 2015, 2016a; Reid interview, [d]Fernández-Giménez et al., 2019a; Reid interview, [e]Fernández-Giménez et al., 2019c; Fernández-Giménez interview; [f]Kassam, 2010; Robinson et al., 2010; Kassam et al., 2011, 2018; [g]UNDP, 2019).

cooperative agricultural research within the lead government agency (USDA-ARS); (2) participatory agricultural research (Uphoff, 1986); and (3) the collaborative adaptive management literature (Susskind et al., 2012; Beratan, 2014). These traditions inspired: (a) inclusion of ranchers, conservation organizations, and government agencies throughout all stages of the ranch-scale, long-term research project, (b) the scale and structure of the project's experimental design, (c) the collaborative and adaptive format of decision-making in CARM; and (d) multi- and trans-disciplinary approaches to research, involving academic, professional and local knowledge of rangeland ecosystems, wildlife, economics, social science, and livestock.

Drought Project, Samburu, Kenya (Pickering, Yasin Interviews)

The Samburu project lasted 6 years from 2014 to 2019 and is a single investigator, multi-county project designed to share pastoral knowledge with powerful NGOs, create co-learning opportunities and contribute to drought planning concerning sheep and goat husbandry. The partnership team was made up of the lead inter-disciplinary researcher (social and ecological scientist) plus 2 main pastoral co-researchers and 10 field assistants. The lead researcher started out focusing on conservation issues, but through long-term consultation with communities, shifted to a focus on women, sheep and goats and drought. The team used the processes of co-production of knowledge, social learning, capacity building, empowerment of voices and reframing the narrative. They think their intangible impacts are inclusion of diverse voices (young warriors, women), creating unique conversations within the community about drought, and building the capacity of Samburu leaders. Their best practices were long-term identification of the research problem through wide consultancy with community members, government and non-profits.

This case study used a collaborative-ethnographic approach (Shirk et al., 2012; Fiske et al., 2014). The team also came into the work with personal ethical stances about the need to listen and collaborate with the community so research would benefit diverse and underrepresented stakeholders in community-based rangeland management (Shirk et al., 2012). In this case, this ethical approach led to three initial field visits to Kenya to consult with NGOs and community members, while making sure to try to include marginalized voices, all to help identify the challenges, most appropriate research questions and methods, and co-interpret some of the results. This was followed by another 2.5 months testing data collection methods and continuing conversations with community members before any data was collected. The full ethnographic research-approach with community focus group discussion methods did not come until toward the end of 9 months of fieldwork (Fiske et al., 2014; Nyumba et al., 2018). Thus the entire research period was a process of checking and re-checking with community members and other stakeholders, with the ethnographic methods added at the end of the research.

Reto Project, Maasailand, Kenya and Tanzania (East Africa, Reid Interview)

The Reto-o-Reto ("you help us, we help you") project started in 1999, was very active for the next 11 years, and continues today. It is an international project, covering the traditional territory of the Maasai people in southern Kenya and northern Tanzania. Its goals were to focus on research identified by community members and policy makers and implement new models of science to support and empower communities (Reid, 2012; Reid et al., 2014b, 2015, 2016a). The partnership team consisted of pastoralists, government managers, conservation NGO practitioners, interdisciplinary researchers in 6 ecosystems and about 100 communities. The problem of focus originated with the community through intensive consultation by the project's "community facilitators" with regular updates and adaptation by the partnership team throughout the project. The partnership had a rapid adaptive learning cycle and measured outcomes with an outcome mapping technique (Earl et al., 2001). They used processes like co-production of knowledge, social learning, capacity building, and empowerment of marginal pastoral voices to reframe narratives about pastoralism. Their intangible impacts included development of confident leaders, building of new institutions and long-term impact on policy through participation on constitution review task forces. Their top best practice was the creation and funding of the team of six Maasai community and policy facilitators, who drove the project to be fully relevant to local pastoral communities and policy makers.

This case study was co-led by a geographer, economist and ecologist, who drew from existing theory when this case began in the late 1990s. At that time, one prominent theoretical framework was power dynamics as expressed in political ecology (Bryant, 1992; Rocheleau, 1995; Akama et al., 1996; Campbell et al., 2005), as well as the growing work in science and technology studies, specifically boundary organizations and transdisciplinary science (Guston, 2001; Klein, 2001; Cash et al., 2003; Goldman, 2006; Wyborn et al., 2019). The work was also informed, like the Kenya case, by the ethical stance of the researchers (Reid et al., 2014b, 2016a). The researchers shared goals to fully include pastoralists as part of the research, to integrate indigenous and scientific knowledge, and to fully connect research and action throughout the work. This work was not explicitly informed by participatory research frameworks or collaborative adaptive management, partly because these areas were less prominent in interdisciplinary science as the work began.

MOR2 Project, Mongolia

The MOR2 (Mongolian Rangelands and Resilience, also "mor" means "horse" in Mongolian) project started in 2008 as a large, 8-year, national-scale project. Its goals were to understand climate and management impacts on rangelands and herder livelihoods, to assess the effects of community-based rangeland management (CBRM) institutions on social and ecological outcomes, and to understand the role of CBRM in system resilience to climatic and socio-economic changes (Fernández-Giménez et al., 2012, 2015, 2017; Ulambayar et al., 2017; Jamsranjav et al., 2018, 2019; Ulambayar and Fernández-Giménez, 2019).

The partnership team consisted of pastoralists, government managers, conservation and livelihood NGO practitioners, and interdisciplinary researchers and worked across 36 counties in 10 provinces of Mongolia. The focal issues originated from a national workshop before the major grant for the project was written, allowing pastoral and governmental priorities to strongly shape the goals of the project. The partnership particularly excelled at inclusion of both Mongolian and American scientists, and the deep reflections about the team science conducted by this project (Fernández-Giménez et al., 2019a). They emphasized processes like intensive social learning and reflection, comprehensive capacity building, integration of knowledges and reframing of narratives about pastoralism. Their intangible impacts were long-term impacts on the scientific team, leadership development and influences on policy. Their best practices included the team science and reflection, yearly meetings with practitioners and government decision-makers at the national level, regional workshops with local and regional decision-makers at the end of the project and evaluation of MOR2 learning opportunities.

The broad MOR2 project was conceptualized using the social-ecological systems framework (Ostrom, 2009), resilience theory (Gunderson and Holling, 2002), the theory of common pool resource governance (Ostrom, 1990; Agrawal, 2002), and non-equilibrium rangeland dynamics theory (Ellis and Swift, 1988). The team science aspect of MOR2 was guided by the science of team science literature and communications theory applied to interdisciplinary research teams (Thompson, 2009). The field research applied a range of different discipline-specific methods including social science interviews and questionnaires, plot-based ecological field sampling, remote sensing, and hydrological measurements which were integrated in a complex databased and through a variety of quantitative and qualitative analysis strategies. Most salient to this chapter/article were the repeated interviews and open-ended surveys of research team members, and facilitated reflective discussions by the team (Fernández-Giménez et al., 2019a).

Co-Creation Project, Spain

This project started in 2018 as a small, 2-year, sub-national-scale project to understand women's pathways into extensive livestock keeping, women's roles as tradition-keepers and change agents in Spanish pastoral systems, and to co-create knowledge for action with women pastoralists. The partnership team consisted of pastoralists, a pastoral network, scholar-activists and interdisciplinary researchers working in 4 regions of Spain including Andaluci̇̃a, Northwest Spain, the Central Pyrenees and Aragón, and Catalunya. The problem emerged out of researcher exploration, experience and awareness of the lack of scientific research on women around pastoralism in Spain, and was refined throughout the project though collaboration with the state-wide network of women pastoralists "Ganaderas en Red" and workshops with them and women pastoralists. This project is unique in that it had an explicit activism goal to support women pastoralists own pathways in their empowerment and social visibility and had strong networking. The team used processes including co-creation of knowledge, networking and empowerment of voices to reframe the scarce and frequently partial narratives about women in pastoralism with social learning as a major outcome. The team hopes their future intangible impacts will be a strong reframing of gender roles and value in Spanish pastoralism, and better social and policy support for women pastoralists. Their best practices included co-creation of knowledge, mutual care and support and their strong linkage to activism (Fernández-Giménez and Estaque, 2012; Fernández-Giménez et al., 2019c).

The Spanish case took a qualitative, constructivist research approach (Moon and Blackman, 2016) but did not adopt a specific theoretical framework at the beginning. Instead, as we worked with the data, we drew on theories of gender in agriculture and natural resources from rural sociology and geography, [e.g., (Whatmore, 1991; Sachs, 1996; O'Shaughnessy and Krogman, 2011; Sachs et al., 2016)], and on feminist political ecology [e.g., (Harcourt and Nelson, 2015)], as they resonated with our data and co-produced findings. We applied a feminist methodology from the outset, aspiring to the following tenets of feminist research. (1) An epistemology that takes knowledge as partial and situated (Haraway, 1988, 1991). (2) Transparency and ongoing reflexivity regarding researchers' positionalities, that is, how our life experiences, social identities, beliefs and values shape our relationships to the research topic, methods and participants (England, 1994). (3) Awareness of power dynamics, an aim to do research *with* not *on* participants, and to demonstrate reciprocity with study participants and communities (Cook and Fonow, 1985; Huisman, 2008). (4) An emancipatory goal that research support participants in advancing their agendas for social change. We realized these principles to varying degrees, by engaging with women pastoralists and/or organizations representing them in research design, data collection, analysis and interpretation, and by reflecting on and interrogating our process within the research team. The most important elements of this were repeated interactions with research participants over time via in-person and virtual workshops, individual correspondence via email and Whatsapp, and continual discussions among the research team throughout the analysis and writing process.

Ecological Calendar Project, Pamir Mountains, Afghanistan and Tajikistan

This project started in 2006 and now is a moderately large, 13-year, international-scale project in 5 villages in the international Pamir Mountains to build trust, co-generate knowledge and create an outcome that is useful to communities to secure their livelihoods and food systems (Kassam, 2009b, 2010; Kassam et al., 2011, 2018). At the core of the project is work on understanding and using ecological calendars of the human body (Kassam et al., 2011). The partnership team consisted of pastoralists and interdisciplinary researchers, and sometimes purposely excluded top-down government involvement. The problem emerged out of researcher exploration and was refined throughout the project through interviews with agro-pastoralists. This project had a strong focus on integration of agro-pastoralist and researcher knowledge and practical use of traditional ecological calendars. The team emphasized processes including co-generation of knowledge, social learning, capacity building, and empowerment of voices to reframe the narrative about agro-pastoralism. Their intangible impacts were development of strong leaders and impact on national climate change policy. Their best practices included the transdisciplinary process (see **Figure 1** below) and their impact on policy.

The primary objective of the Ecological Calendars Project is to develop context-specific adaptive and anticipatory capacity to anthropogenic climate change at the level of villages and towns. Therefore, the objective informed the methodology. The research process in the Pamirs partnership was guided by three theoretical frameworks. The first was participatory action research, which lays out the process for interaction between communities of inquiry (researchers) and communities of social practice (farmers, herders, fishers). This process is the co-generation of insight described in this paper from setting the research agenda, undertaking the research through to implementation of policy action (Greenwood and Levin, 2007). The second framework was transdisciplinarity, which situates the co-generation of knowledge outside the ivory tower of academia (Kassam et al., 2018). The final framework is the recognition of the complex connectivity between biological and cultural diversity which facilitates the co-generation of knowledge and transdisciplinarity based on the foundation of the ecological habitat (Maffi, 2001; Harmon, 2002; Kassam, 2009a).

Case Summary and Comparisons

Overall Biophysical and Social-Economic Characteristics

Our cases span tropical (Kenya, Tanzania), Mediterranean (Spain), and temperate zones, from mountains (Pamirs, Spain) to savanna and woodlands (East Africa, Spain) to steppe (US, Mongolia) and semi-desert (Mongolia, Spain; **Table 1**). The Spanish cases cross a huge range of precipitation, encompassing the rainfall ranges of most other cases. The cases are part of countries that have Human Development Indices that vary from low (Tanzania, Afghanistan) to medium (Kenya, Tajikistan) to high (Mongolia) to very high (Spain, US). Most of the sites are home to transhumant pastoralists, who move among 2-4 seasonal pastures. Even the US ranching system can be considered transhumant (Huntsinger et al., 2010) although ranchers don't often move their households seasonally as often seen elsewhere. There is more private land ownership in the US and Spanish cases than elsewhere, but even US ranchers, if they graze federal land, do not control all the land where they graze their herds (Huntsinger et al., 2010). From case to case, ethnic diversity varies from low (US, Mongolia), to moderate (Kenya, Tanzania, Mongolia, Spain) to high (Tajikistan, Afghanistan).

Driving Forces, Composition, Size, Leadership Goals

All of these partnerships sought to address emergent complex problems through transformation, and all had elements of "strange bedfellow" or "unlikely" alliances (Hillis et al., 2020). All the cases created informal or formal partnerships with membership including pastoralists/pastoral communities and disciplinary/inter-disciplinary researchers (**Table 1**). The larger partnerships expanded their engagement to include government managers and NGOs (Colorado, East Africa, Mongolia, Pamirs). Projects differed significantly in their size, with the Mongolia project stretching across a full nation and involving 5 disciplines, lasting 8 years. In contrast, another partnership by the same lead researcher was in Spain, worked in 4 sub-national regions with 3 disciplines. All cases were led by either disciplinary or interdisciplinary researchers and emphasized co-production/co-generation and social learning as a key and transformative process in their work. Important to all partnerships was a focus on the process of partnership engagement and co-generation of knowledge, which was even more important than partnership outcomes and impacts. Partnership goals consisted of a diverse set of research goals, like drought, gender, animal production, and some had explicit partnership goals, like co-creation of knowledge (several), developing community-driven research problems (East Africa), and creation of useful outcomes (Pamirs).

Partnership Outputs: Processes and Products

Our cases created both processes and products as outputs (**Table 1**). Process outputs included creating collaborative research and action teams; integrating diverse experiential, Indigenous, local, practical, technical and research knowledges; co-production/co-generation/co-creation of new knowledge together; social learning to understand issues and recommend action; building capacity of all team members, but especially pastoral community members; building strong research and action networks; and implementing management practices and promoting new governance structures and policies. Product outputs consisted of an array of communication products (theses, publications, reports, oral presentations, websites, evaluations), education materials (training manuals, training courses, university curricula), learning and networking opportunities (peer-to-peer pastoral visits, field visits, conferences, research and community feedback workshops, policy meetings, retreats), social events (national holidays, award celebrations, meals together), and technology transfer (a vaccine and a better bull) and a new non-profit organization.

Outcomes, Long-Term Impacts

We will discuss these aspects of our cases in the section on outcomes and impacts that follows the definitions section below.

KEY DEFINITIONS, CRITICAL CONCEPTS AND PROCESSES

Key Definitions

Science With Society and SWS Partnerships

The approach taken by the partnerships here has many abstract and unclear names in the literature and in practice, as described above. We prefer to use a name for this approach that it is clearly understandable, strongly implies linked research and action, and is powerful. Thus, we avoid calling this approach "transdisciplinary research" since it is an abstract term and unclear. We use the word "science," rather than "research," because of the implication of power in the word "science." We then define "science" broadly to include several areas of inquiry including western science, Indigenous science and humanities research. Then, we prefer the phrase "science *with*

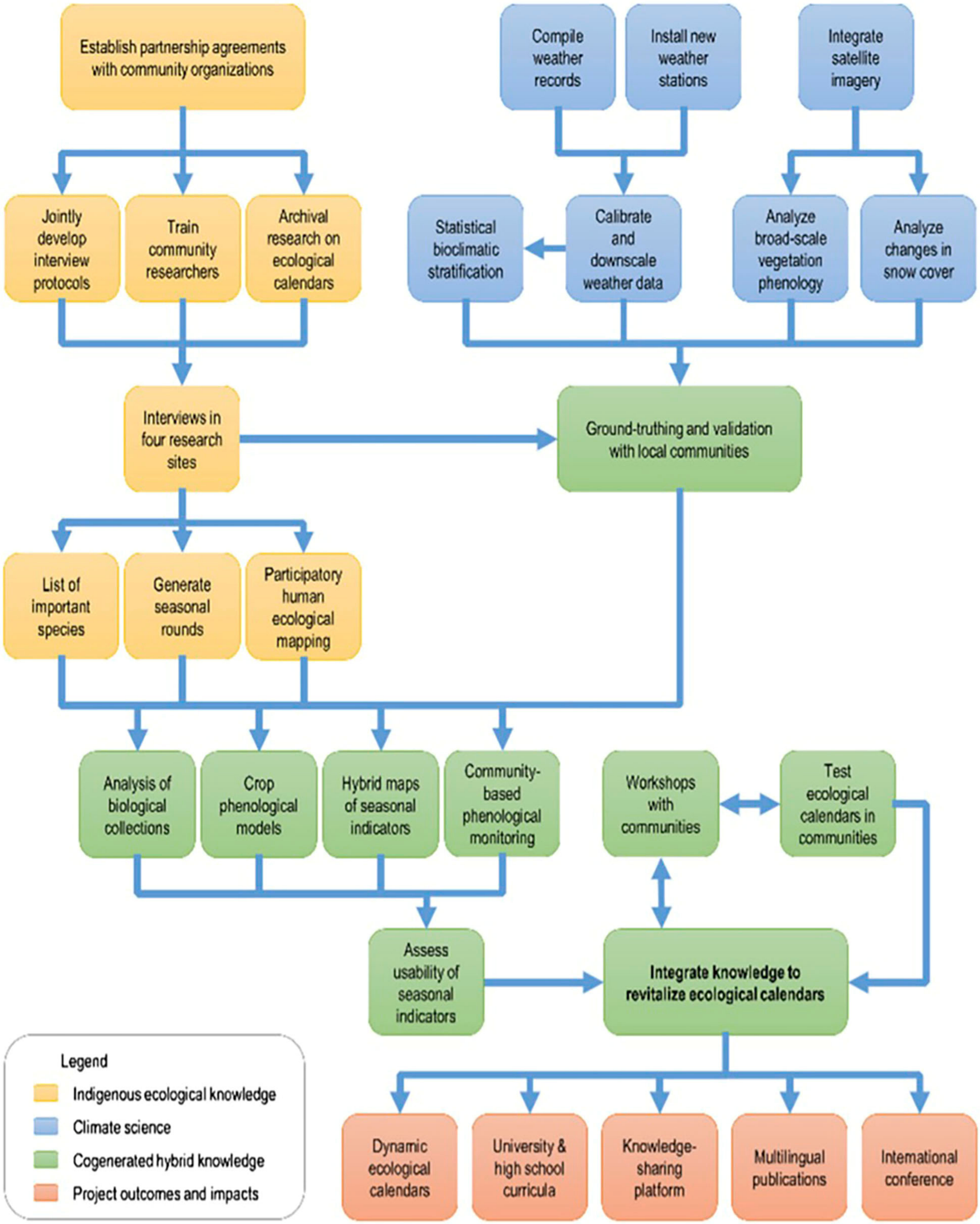

FIGURE 1 | Transdisciplinary research process and knowledge integration in the Pamir's case, Afghanistan and Tajikistan [from Kassam et al. (2018)].

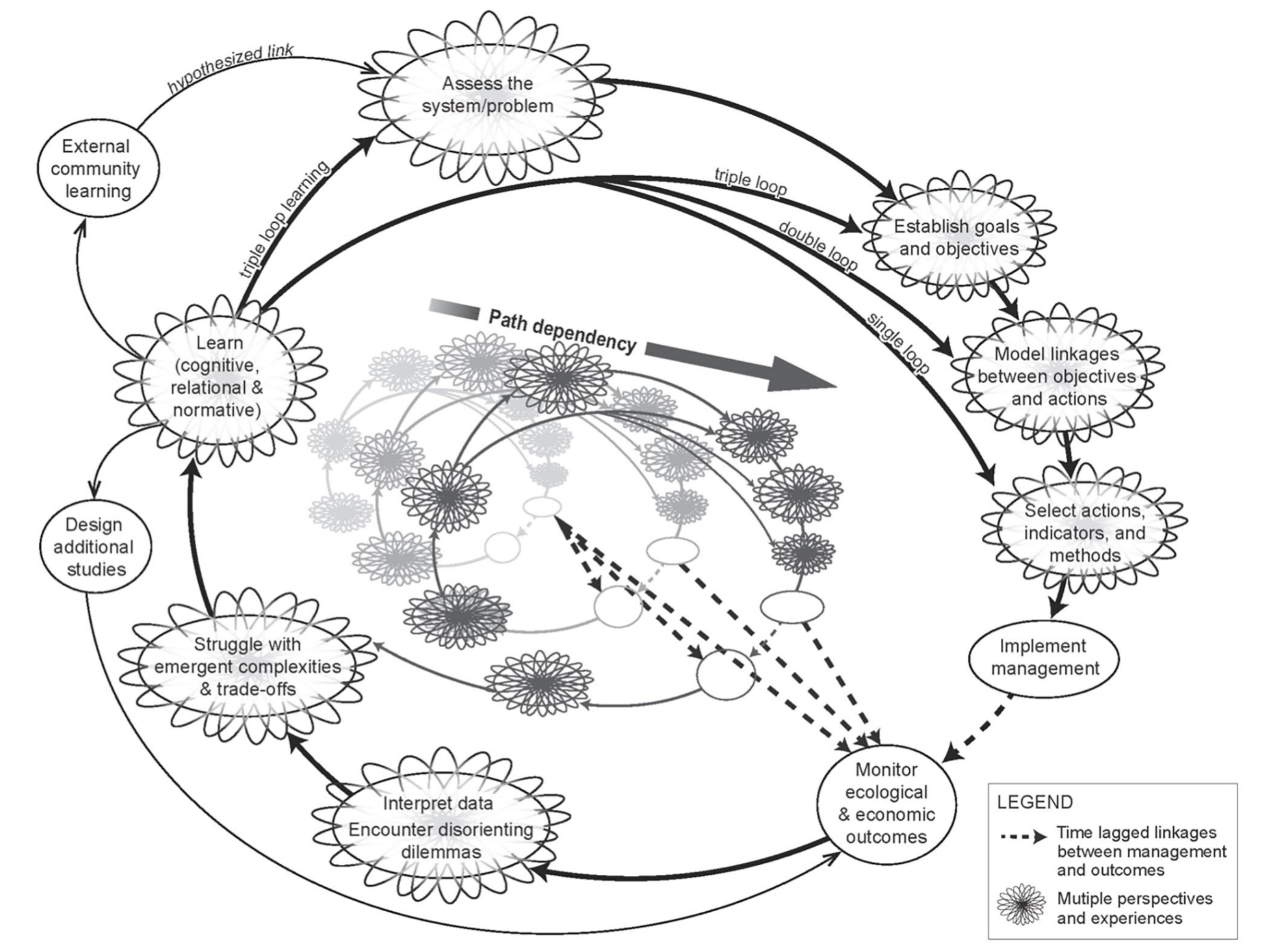

FIGURE 2 | Collaborative adaptive management cycle undertaken by the Colorado (CARM) case, showing single to triple loop learning, as well as disorienting dilemmas, emergent complexities, trade-offs and path dependency, figure from Fernández-Giménez et al. (2019b).

society" [after (Seidl et al., 2013)] rather than "science *for* society" to strongly imply the co-creation process with use of the word, 'with'. Then this paper is about "science with society (SWS) partnerships." The "community of inquirers" (Kassam et al., 2018) are then both scientists and researchers. Then the "communities of practice" are "practitioners" and "actors" which include pastoralists, ranchers, conservation practitioners, government managers, business people, and regular citizens. Of course, as described here, there are hybrid categories in these communities, including "pastoralist-scholars," "scholar-ranchers," "pracademics," "practitioner-scholars," "scholar-practitioners," and "scholar-activists," just as there are, within science, interdisciplinary "social-ecological" scientists.

How Interdisciplinary and Transdisciplinary Research Relates to Science With Society

Like (Klein, 1990), we define *interdisciplinary research* as the use of more than one scholarly discipline to address a research issue, including attempts to integrate different disciplines into new forms. *Transdisciplinary research*, often also interdisciplinary, is defined as science that brings together research with society, "transforming" the research problem (Pohl and Hirsch Hadorn, 2008) and its potential solutions. In this paper, we substitute the term, "science with society," for the terms, "interdisciplinary research" and "transdisciplinary research," because the former is clearer and more powerful. Science with society (or SWS) initiates a transformation process that includes: "societal agenda setting, collective problem framing, a plurality of perspectives, integrative research processes, new norms for handling dissent and controversy, in-depth treatment of uncertainty and of diversity of values, extended peer review, broader and more transparent metrics for evaluation, effective dialog processes, and stakeholder participation" (Cornell et al., 2013):60. This approach "goes beyond the 'primacy of science' as well as the 'primacy of practice', establishing a third epistemic way" (Lang et al., 2012):26. Our cases all take an SWS approach since they all address linked social, economic and ecological issues of importance to society (interdisciplinary) and engaged with members of society throughout the SWS process (transdisciplinary).

Key Processes in Science With Society

Of these general processes of SWS globally, we will define and dive into the concepts of the seven processes that were important to our rangeland cases here, which appear as "partnership process outputs" in **Tables 1**, **2**. The first process is *building collaborative relationships* with a goal to build trust, create more inclusion and respect, empower marginalized voices, create collective buy-in for project outcomes, and create a convening platform for collaborative work together. Relationships are the core of this approach and are important to its short and long-term success. The emphasis on relationships is important because it shifts the foundation of this work from an underlying model of neoliberal Western culture to the more global, cross-cultural model of relationships and collectivism. For example, in our Mongolia case, the leader of the research team worked for years as a single researcher in the field, slowly building relationships with communities and government. She then created the MOR2 project, with a highly interdisciplinary team, and started the project by bringing together these researchers, community members and government officials in an intensive workshop to design the research so it answered key community and policy questions.

Here, our cases often fall under a broad definition of the second process, *co-production (or co-generation),* which is a process "that iteratively brings together diverse groups and their ways of knowing and acting to create new knowledge and practices to transform societal outcomes" (Wyborn et al., 2019):322. Co-production has at least four aspects: material (what is), normative (what should be), cognitive (what we think) and social (what we do) (Wyborn, 2015). Each of the cases here used some aspect of co-production in their research process.

A note of caution here: (Chambers et al., in review), looking across 32 co-production cases around the world, found that co-production was the only outcome that delayed accomplishment of other outcomes. They think this is because co-production "overly fetishizes the role of delivering scientific knowledge to create change and legitimizes researchers' control of the process." This then slows down achievement of other outcomes. They recommend that collaborative work focus on shaping relations, practices, and institutions, with knowledge production playing an integrated role in those processes.'

Here, we take a broad view of the co-production process to put science and action on equal footing. Researchers can tend to put high value on "expanding the knowledge base," when the action outcomes are often more important to community members and practitioners (Lang et al., 2012). Practitioners can tend to put more emphasis on action and devalue research. To avoid these two pitfalls, we see co-production for what it is meant to be: a purposeful linking of knowledge and action together with strong feedbacks. Here, the CARM and East African cases used repetitive reflection and planning meetings, sometimes monthly, to align the incentives and goals of research and action. Thus, co-production is the entire collaborative process, where collaborative practices lead to expanding the knowledge base and increased capacity which then leads to action (and outcomes and impact) affecting well-being, rangeland health, policy, services, products, funding and institutions (Wyborn et al., 2019). In this framework, co-production is nested within ever-larger spheres of context including communities and stakeholder groups, existing systems of policy and institutions, and social and cultural norms.

In practice, in our view, the next two processes in our cases, *knowledge integration* and *social learning*, are the heart of successful co-production of knowledge with action. The broadest or most general type of knowledge is Indigenous or traditional knowledge which includes empirical, practical, normative, purposive and spiritual knowledges, and practices and beliefs (Berkes, 2009; Pickering Sherman and Sherman, 2010). Western knowledge can be broken down into western scientific knowledge (e.g., physics economics, sociology, ecology), practical knowledge (e.g., engineering, medicine, rangeland management), normative knowledge (e.g., law, planning, politics) and purposive (e.g., ethics, values, philosophy) (Max-Neef, 2005; Reyers et al., 2010; Tengo et al., 2014).

Our cases all "bring together" different knowledges, principally diverse pastoralist knowledges and interdisciplinary researcher knowledges, and some also integrate knowledges from conservation practitioners, government managers, policy makers and/or activists. In the Pamir's case, Kassam and team provide rich detail (Kassam et al., 2018) of the independent knowledge domains they brought together (Indigenous and climate science) and what hybrid knowledge they co-generated together (crop models, ecological calendars of the human body). They also specify the practical, educational, networking, and scientific outputs from that integration (**Figure 1**).

Social learning is "a change in understanding that goes beyond the individual to become situated within wider social units or communities of practice through social interactions between actors within social networks" (Reed et al., 2010):6. Social learning is thought to occur in multiple loops, resulting in progressively deeper reflection and change in an individual or group as they learn (Keen et al., 2005; Fernández-Giménez et al., 2019b). Single loop learning is about cause and effect, double loop learning addresses our assumptions or mechanisms (how things work) and triple loop learning can revise our values, norms and actions (Fernández-Giménez et al., 2019b). These learning loops occur within science, within practice and between science and practice (Lang et al., 2012). Triple loop learning can be simplified into three stages: a disorienting dilemma, critical reflection and reflective discourse (Pennington et al., 2013). Here, we treat social learning as a process output, but it can also be considered an outcome.

Our Colorado case used the collaborative adaptive management cycle which we will use here to illustrate how to embed social learning with management experimentation and action (**Figure 2**) (Fernández-Giménez et al., 2019b). This cycle was tested by a team that experimented with contrasting grazing strategies to improve cattle weight gain and grassland bird diversity. They found that they had to adapt a simple adaptive learning cycle into one with more complexity, as depicted in

TABLE 2 | Seven types of impact pathways as a result of process outputs partners implement that form a 'process' a theory of change for our rangeland partnerships.

Partnership process output (from Table 1)	Outcomes (2–5 years)	Desired action/impacts (5–10 years)	Intangible long-term impacts (20+ years?)	Which case achieved what?
1. **Collaborative relation -ships:** Team convenes diverse collaborative group that builds relationships	Stronger trust & relationships, more inclusion & respect, re-framed narrative, empowered voices	Continued collaboration by **diverse teams** on big issues; community takes leadership role	Confident leaders have big impacts, team members work together on new projects, less polarization, decolonization	Outcomes: All cases Impacts: EA,M
2. **Knowledge integration**: Team brings together local, indigenous & research knowledges, reframes story	**Govt, NGOs** see value in integrating & using diverse knowledges to identify problems & needed action	**Govt, civil society** use integrated knowledge to develop policy & practice that supports pastoralism	Pastoral livelihoods & rangelands are healthier & more resilient; marginalized pastoral voices respected & supported	Outcomes: All cases Impacts: EA,M,P
3. **Co-production:** Team creates knowledge that is relevant and useful for **community, NGOs, govt**	**Govt, NGOs** consider co-prod knowledge when planning future work	**Community** uses evidence on mgmt practices, **govt, NGOs** develop policy & practice that is more evidence-based	Research-action networks change how science gets done & policy developed, networks support activism for policy change	Outcomes: EA,M,P,C Practice Imp: C Policy Imp: EA,M,P
4. **Social learning:** Team learns together and jointly problem solves	**Team members** change their mental models & vision of the possible & influence others	**Team members** implement learning process & new mental models in policy &/or practice	Mental models and transformative learning catalyzes systems, values & science to transform	Outcomes: All cases Practice Imp: C Policy Imp: EA,M,C
5. **Capacity:** Team builds capacity of all members	**Pastoral members** become robust voice for team & stronger leaders; **researchers** change how they do science	**Stronger leaders** create more inclusive policy & practice supporting pastoralism & healthy rangelands	Inclusiveness & justice becomes the norm, pastoralists sit at the tables of power; science becomes decolonized & democratized	Outcomes: All cases Impacts: EA,M
6. **Networks:** Team strengthen pastoral-researcher-action networks	**Network** becomes known and relied upon & expands to new members	**Network** influences policy & practice	Networking becomes the norm & helps transform systems, less polarization	Outcomes: Spain, M,C Impacts: None
7. **Implement action:** Partnership implements mgmt practices, promotes new governance	**Govt, NGOs** use partnership's best practices /or governance/climate change recommendations	**Ranchers** implement practices that better support household economies & rangeland health; governance improves policy	Action with research the norm, new institutions and policy improve pastoral livelihoods & rangeland health	Outcomes: C,EA,M Mgmt Imp: C Governance/climate: EA,M,P

Cases: C, Colorado[1]; K, Kenya[2]; EA, East Africa[3]; M, Mongolia[4]; S, Spain[5]; P, Pamirs[6]; Imp, Impacts.
[1]*Wilmer et al., 2018, 2019, Wilmer interview, Fernández-Giménez et al., 2019b, Porensky email;* [2]*Pickering interview;* [3]*Reid et al., 2014a,b; Reid et al., 2016a,b, Reid interview;* [4]*Fernández-Giménez et al., 2019a;* [5]*Fernández-Giménez et al., 2019c, Fernández-Giménez interview;* [6]*Kassam et al., 2011, 2018, Kassam interview.*

Figure 2. The team gained key insights from using this approach including encountering disorienting dilemmas which challenged their mental models with trade-offs and emergent complexities (Fernández-Giménez et al., 2019b). *Disorienting dilemmas* (Pennington et al., 2013) occur when participants encounter experiences and information that causes them to struggle and then replace their existing concepts with new ones, creating new *mental models*. Mental models are how we represent the world around us in our minds and form the basis of our decision making (Jones et al., 2011; Fernández-Giménez et al., 2019b).

Our last three processes are capacity building, networking and implementing action. The goal of the fifth process, *capacity building*, is to support participants in an SWS partnership to develop and refine the knowledge and skills to build and support strong SWS teams, to respectfully and thoughtfully engage with each other on those teams, and to negotiate how to work together and resolve conflict. This capacity applies to all members of the partnership from pastoralists to researchers, from the most senior to most junior member. We also found, particularly in our Mongolia and East Africa cases, that this capacity building was critical to long-term impacts on policy and practice. The sixth process, *networking*, means both informal social networking but also establishment and expansion of more formal networks. In the Spanish case, for example, the networking between the "ganaderas" (women pastoralists) and the researcher who worked in Mongolia and the US made the ganaderas feel they were part of a wider, international context. The last process is *implementing action*. This means engaging in action activities like changing a management practice, restoring land, and, in a more distant way, participating in policy and practice design workshops that lead directly to action implementation.

Finally, *boundary spanning,* which is not a process output in **Table 1**, is another key process in SWS that facilitates the co-production of knowledge by individuals, disciplines, sectors, organizations and across scales. This concept was originally applied to "boundary organizations" which are intermediaries that are accountable to both sides of organizational boundaries and convene, mediate, and negotiate among different stakeholders (Guston, 1999; Cash et al., 2003, 2006). The practical idea of a boundary organization is to reduce the cost of co-production and partnership building (Lemos et al., 2018). Boundary "partners" are those a program interacts with directly and hopes to influence (Earl et al., 2001). Boundary spanning individuals have a key function as apolitical intermediaries who serve as catalysts for a collaborative process (Barry et al., 2007; Hillis et al., 2020) and link disciplines, institutions, and scales (Reid et al., 2016b).

In our Spain and Kenya cases, both lead researchers were disciplinary boundary spanners as interdisciplinary scientists, mastering both ecological and social science disciplines and methodology. Another member of the team in the Spain case might be considered a boundary spanner as scientist and activist, as co-facilitator of the network of women pastoralists. In our other cases, most of the disciplinary scholars also took on boundary spanning roles by working with pastoralists, with other disciplinary scientists, and among different institutions. In the East Africa case, the entire research-and-pastoralist team was based out of a boundary spanning organization (the International Livestock Research Institute) and each member of the team had explicit boundary spanning roles with communities, policy and across scales (Reid et al., 2016b).

Boundary spanning roles for researchers become more complex and diverse as disciplinary research becomes interdisciplinary, then transdisciplinary and potentially transformative (**Figure 3**). As research goes from the inner to outer rings in **Figure 3**, it becomes more relevant to real world problems, more inclusive of different ways of knowing, and more political and value driven. Each successive ring, we would argue, transforms how science is done and how much it supports action by a wide range of actors and practitioners. It was only after reaching the third outer ring, for example, that our Pamirs, Reto and Mongolian cases started to have impacts on national policy in Afghanistan, Mongolia and Kenya. We will return to this figure in the last section of this paper.

Outputs, Outcomes and Impact

One of the biggest questions about these labor-intensive partnerships is this: Is all this effort worthwhile? Commonly, partnerships keep track of their *outputs* (knowledge, fora, and processes generated by partnership activities), their *outcomes* (changes in knowledge, skills, attitudes and relationships that cause changes in behavior of the partnership's clients or the environment) and their *impacts* longer term effects of the partnership's outcomes on society and the environment; modified from Earl et al. (2001), Belcher et al. (2019) (**Table 1**). Here, *outputs* include not only hand-tangible products, such as a map or a conference, but also processes, such as co-production or capacity building. We like this broad definition of outputs because processes often lead to important, long-lasting outcomes and impacts, even more than tangible products do, as we will see below in **Table 2**. Next are *outcomes*, which often occur in the first 5 years of the partnership. *Impacts* occur after outcomes and are more indirect, as a consequence, their cause attribution is difficult at best (Koontz and Thomas, 2006). Also, this chain of influence can create both positive and negative impacts and those can differ by different actors (Hillis et al., 2020). We will dig deeper into the outcomes and impacts of our cases in the next section.

Transformations, Transformative Agency/Action and Transformative Learning

Once achieved, when do outcomes and impacts become transformative? Here, we define a *deliberate transformation* as the creation of "a fundamentally new system when ecological, economic, or social structures make the existing system untenable" (Walker et al., 2004): 5. Partnerships deliberately work together to transform some aspect of a problem they tackle, and sometimes eventually cause their social-ecological system to cross "thresholds into new development trajectories" (Folke et al., 2010): 20. A transformation can be a tangible change, like a new policy, management practice or network, but also a more intangible change in ideas (Heikkila and Gerlak, 2019; Hillis et al., 2020), processes, learning (Pennington et al., 2013) and leadership that helps individuals and communities to build a better life (O'Brien, 2012). It can also be a change that allows researchers to do more creative, intellectually stimulating and impactful work (Pennington et al., 2013). We think that one of the most transformative aspects of partnerships is that they change the conditions that hold systems in place by changing paradigms to reconstruct power relations, build relationships and change mental models. All of our cases did this, exemplified by the CARM case, where researchers shared their expert power with ranchers and, together, the team built strong relationships and shifted their mental models of the world.

Transformative learning is a key part of transformation processes, often defined by triple loop learning (Mezirow, 1991). Social learning, a broader term, can lead to no change, incremental change (or an adaptation) or to a larger, transformative change. *Transformative learning* consists of an individual's ability to examine their own assumptions through critical reflection and open-mindedness, and the ability to listen to and take in perspectives and viewpoints different than their own (O'Brien, 2012). This also requires a respect for and desire to understand information from different knowledges. For example, this can include attempts to make science more inclusive of other knowledges by decolonizing the western European cultural assumptions underlying scientific methodologies (Smith, 2002). Transformative learning and willingness to experiment can play

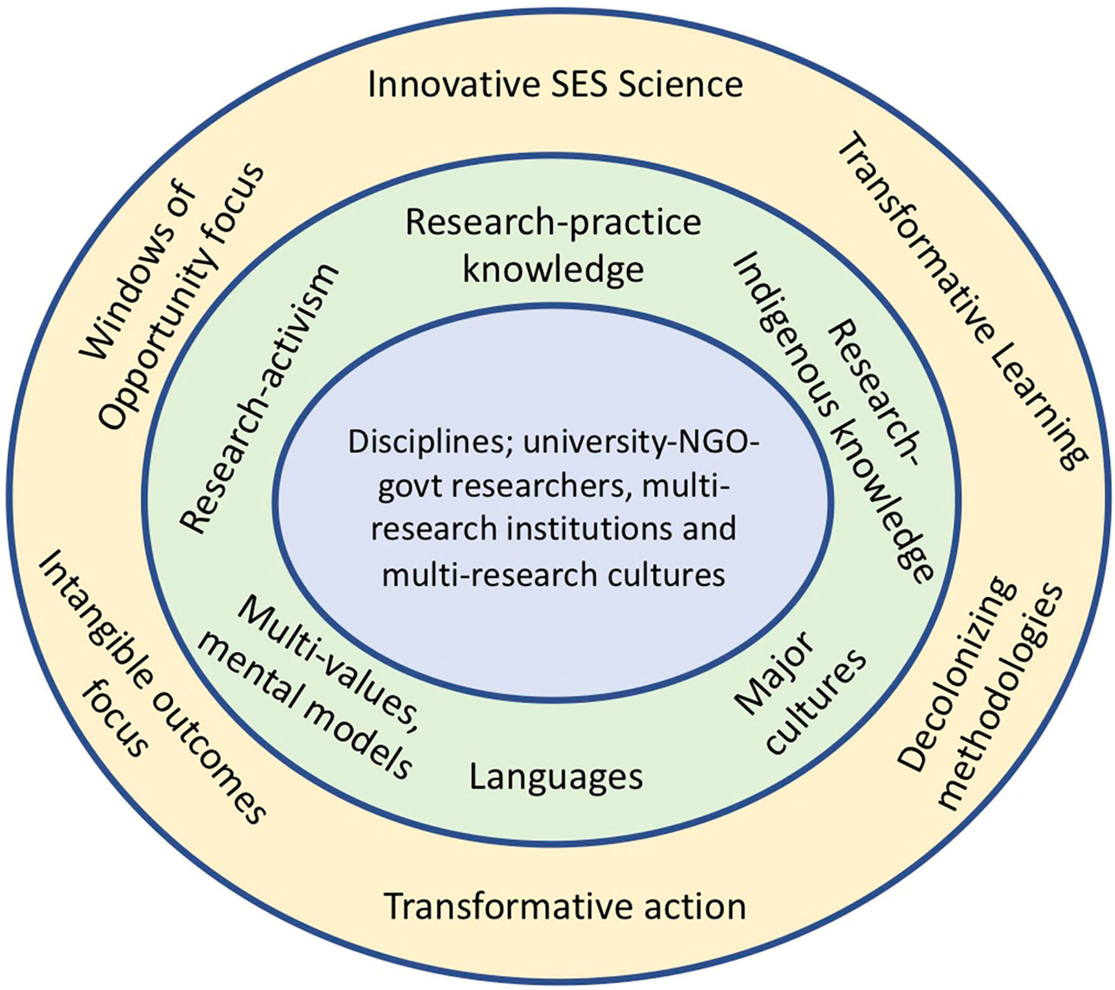

FIGURE 3 | The increasing complexity of boundary spanning when moving from interdisciplinary (blue center circle) to science with society (green middle ring). The outer orange ring is not boundary spanning, but rather the next evolution of the practices/strategies that could make science with society more transformative.

a role in systems transformation (Tschakert and Dietrich, 2010), like in our Colorado case.

System Transformations

How, when and why do systems transform? Gunderson and Holling (2002) describe the adaptive cycle of social-ecological systems, as a cycle from conservative, slow moving systems exhibiting incremental change to young, fast moving systems that exhibit rapid change, all connected in an adaptive cycle. Mature systems can rapidly transform if there is a *trigger* that creates a *window of opportunity for transformation* creating a specific moment in time to act (Olsson et al., 2006, 2017; Biggs et al., 2010). A window of opportunity opens when three things are in place: a group recognizes a problem, there is a solution at hand and there is the political will to implement it (Olsson et al., 2006). Thus, in that window, *institutional entrepreneurs* (Westley et al., 2013) in a collaborative partnership need to know what *leverage points* to use to catalyze fundamental and transformative change (Abson et al., 2017; Fischer and Riechers, 2019). Leverage points are "…places within a complex system (a corporation, an economy, a living body, a city, an ecosystem) where a small shift in one thing can produce big changes in everything" (Meadows, 1999):1. A leverage point that changes a policy constraint will have less impact than a leverage point that addresses a more fundamental change in mindsets, values or paradigms.

In rangelands systems, for example, a window of opportunity (outer ring, **Figure 3**) often forms when there is a crisis (*trigger*) that brings together diverse stakeholders (like ranchers and conservation organization professionals) around a big problem of common concern (Hillis et al., 2020), like a wildfire, water conflict, new extractive industry, or an impending regulation. Or it can occur when major new policy is implemented. Important for a system transformation is the role of a *social innovation*, which is "a new program, policy, procedure, product, process and/or design that seeks to address a social problem and to ultimately shift resource and authority flows, social routines and culture of the social system that created the problem in the first place (Westley et al., 2011)" (Westley et al., 2017):4. *Institutional entrepreneurs* can recognize a major window of opportunity and use this leverage point and the social innovation of a new policy to transform a pastoral system (see **Table 1** for case examples).

OUTCOME AND IMPACTS OF THESE SWS PARTNERSHIPS: WHAT ARE THEY AND ARE THEY TRANSFORMATIVE?

Theory of Change: Connecting Partnership Process Outputs to Outcomes to Impacts

We developed a generalized "theory of change" based on our six cases, starting with the processes the SWS partnerships implemented and flowing through a sequence of outcomes, desired action/impacts to very long-term and less tangible impacts that we suspect will form decades after our work together (**Table 2**). A theory of change shows how the work contributes to a change process and the main actors involved, and can be used to track and evaluate partnership impacts over time (Belcher et al., 2019). Here, we focus on the positive aspects of these partnerships, with the recurring challenges of partnerships in the last section of this chapter. In addition, it is possible for any of the sequence of changes shown for the seven processes in **Table 2** to be fully negative, however unlikely, leading to suppression of voices or more polarization, if participants are not ready to collaborate, or if the partnership is not carefully facilitated. More likely are partnerships that are too short term to solve problems because of the extra time and resources needed to make these partnerships successful (Hillis et al., 2020).

Our cases implemented most of seven important (and often sequential) processes, which we are calling *process outputs*[2] (**Tables 1**, **2**), which can also be thought of as social innovations, through process, sometimes aimed at particular leverage points. First, all cases engaged in a *collaborative relationship-building* process as an early step. Each partnership brought together participants with different values who had different social networks and held different political and religious beliefs. Some were from different nations, spoke different languages and were of different races. Thus, listening to each other, eating together, and becoming close colleagues (and often friends) was foundational to their partnership. It is also the most long-lasting part of many partnerships. These relationships developed outcomes of trust, inclusion and respect, and importantly can empower voices of marginalized pastoralists to be heard by other participants. In the East Africa case, this empowerment was a main goal of the partnership (Reid et al., 2016b). All our longer-term cases (Colorado, Pamirs, Mongolia, East Africa) found that these outcomes can lead to continuing impacts as partners come together on other projects over time, building on the lessons of their initial work (Kassam & Reid interviews).

All our cases also *integrated existing knowledge*, including some combination of Indigenous, traditional, experiential, local, practical, management and/or western scientific knowledges. In some cases, this integration "reframed the story (or narrative)" that pastoralism was considered primitive, backward and degrading to the land (Reid pers obs) or the role of women in pastoralism (Spain, Kenya). This sometimes led government, civil society and businesses (East Africa) to recognize this knowledge and to develop policy and practice supporting what they learned from pastoral-researcher knowledge (**Table 2**). In the Pamirs, the SWS partnership documented the importance of ecological calendars of the human body and brought this information to the attention of national policy makers, who then implemented new climate change policy based partly on this research of integrated agro-pastoral-research knowledge (Kassam interview & report). In the East Africa case, the team highlighted pastoral knowledge that suggested that, contrary to the dominant story about pastoralism, livestock attract wildlife by creating short grassy areas where wildlife can see lions approaching. This "reframing" of the narrative by integrating knowledges provided a new narrative supporting the widespread establishment of pastoral-led governance of wildlife in community conservancies [(Reid et al., 2016a), Reid interview]. This reframing was often voiced by community members when pastoral leaders led discussions in the East Africa case (Reid interview).

All of our cases also *co-produced/co-generated new knowledge* together. Our Kenya case started with intensive and repeated visits with Samburu pastoral communities, NGOs and government officials to determine how the research could be useful to their needs. The lead investigator, Pickering, entirely shifted his research focus, from community conservation to drought, in response to these consultations (Pickering interview). Our Spain case started with research issues identified by scholar-activists on the core team, but quickly engaged female pastoralists in interpreting interview and documentary information about their lives (Fernández-Giménez et al., 2019c). For all our cases, another key process was co-interpretation of the meaning of new knowledge during feedback workshops, reflection meetings, informal conversations and retreats. These enabled new knowledge to be more robust, more relevant, and locally owned by pastoralists and ranchers. In Mongolia, co-produced knowledge may have impacted policy development through the many meetings project members had with policy makers during the project and after it ended [(Fernández-Giménez et al., 2019a), Reid interview].

Social learning was more deliberate in some of our cases than others. Our Mongolia and Colorado cases deliberately added social learning to their project objectives and then took many opportunities to meet and reflect on their progress, their mental models, and their teamwork (Fernández-Giménez et al., 2019a,b). Our Colorado case used the collaborative adaptive management cycle which we will use here to illustrate how to embed social learning with management experimentation and action (**Figure 2**) (Fernández-Giménez et al., 2019b). This cycle was tested by a team that experimented with contrasting grazing strategies to improve cattle weight gain and grassland bird diversity. They found that they had to adapt a simple adaptive learning cycle into one with more complexity, as depicted in **Figure 2**. The team gained key insights from using this approach including encountering disorienting dilemmas which challenged

[2] But social learning could also be considered an outcome.

their mental models with trade-offs and emergent complexities (Fernández-Giménez et al., 2019b). Even though our other cases did not highlight changing mental models as an outcome, the descriptions of their work indicate that this is a likely outcome for them as well.

In the Kenya case, social learning was important but not as deliberately evaluated. Co-author Yasin described their learning this way: "*The best research gets diverse voices from the community, for instance in Samburu different age-sets and genders come together and learn from one another as the researcher shares information in these discussions. These discussions among diverse community members would not otherwise come together. They also will have many side discussions and continue to share information among themselves. Furthermore, these interactions build trust among different community members.*" (Yasin interview).

Perhaps the most far-reaching outcomes and impacts of our cases is when they formally or informally *built capacity*. This can be capacity of any participant, a pastoralist, a student, a scientist, a government manager or an NGO practitioner. Which participant was involved determines what realm the stronger capacity affects.

For example, students either leading (Kenya) or working on (Colorado, East Africa, Mongolia, Pamirs) our cases continue to have impacts on pastoral policy, management practices and how science is done. The Kenya case is led by a non-pastoral non-Kenyan. His impact will probably affect development/conservation practice in his future work and has already impacted how he thinks about and does science (Pickering interview). The East Africa, Mongolia and Pamirs cases all facilitated pastoralists from local communities (or pastoral nations like Mongolia) to complete their graduate degrees at universities in-country and around the world. In the East Africa and Mongolia cases, those students who finished their degrees more than 4–5 years ago are now major, established leaders in government, business and NGOs who influence policy and practice concerning pastoral development, climate change and conservation in their countries (Reid et al., 2014b, Reid interview). These former students are drawing from their experiences in our co-produced work, as well as many other influences in their lives, to make major changes in policy and practice. Pickering, describing the capacity of his pastoral team leader (who is not yet a graduate student), described it this way: "*I'm very impressed with the individual he (our pastoral team leader) has become ....how he takes an active role in his community. He has learned from conducting and advising our research project how research and discussions can be used to learn with community members. He has combined this with his social, environmental, herding, and pastoral insights into Samburu life to help others. He knows how to bring in all those perspectives and bring people together to identify research, understand the science, and solve bigger issues in his community.*" In the Colorado case, one of the students on the project is a rising star in government-led science. Her prodigious experience in co-production and deep reflection on process will likely influence all her future work on government practice and science (Reid pers obs).

Another important process is the *establishment and expansion of networks*, which can be formal or informal. All our cases built and supported less formal social networks. Our Spanish case explicitly connected to and provided information to a more formal network of women pastoralists called Ganaderas en Red (GeR). Project leader Fernández-Giménez describes the impacts of their workshops: "*Although they can't be attributed solely to this project, the workshops we facilitated with (the) GeR (network) helped strengthen women's networks, self-esteem/confidence, and clarify their agenda for action.*" In this case, the pastoral women who were part of the GeR network are very committed to broad-scale social transformation of food systems and rural communities. The team's research supported the network's goal by studying and raising the visibility and profile of women pastoralists as both tradition-keepers and change agents in rural livestock systems (Fernández-Giménez et al., 2019c, Fernández-Giménez interview).

A few of our cases had the process goal to *implement action*. Our Colorado team focused all of their work on implementing a grazing experiment. Because other stakeholders see this experiment (and ranchers look over the fence at it), it is not a stretch to say they implemented action, and this is having outcomes. In East Africa and Mongolia, the action is mostly implemented by pastoral leaders whose capacity was built during the course of our co-produced research. In the East Africa case, pastoral community facilitators (many of whom were also getting advanced degrees on the project) worked closely with communities to bring in more drought resistant cattle breeds, new vaccines for East Coast fever and more sustainable water pumping technology. After they finished their community facilitation positions, one became a national NGO CEO, leading a community conservation governance revolution in Kenya (Reid et al., 2016a). Another pastoral leader was elected governor, designing and executing pastoral policy for a million pastoralists and then became a water minister for the country of Kenya (Reid et al., 2014b, Reid interview). While our co-produced work together is far from the cause of the major impacts of these pastoral leaders on their country, our work did contribute to building their confidence and allowing them to see the value and limits of research through their advanced degrees on our projects (Reid et al., 2014b). The outcomes and impacts of the implementation of these actions by SWS partnership participants are likely far-reaching.

Intangible Impacts

Kassam, the leader of the Pamir's case, makes a strong argument that impacts go beyond the tangible to the intangible (Lang et al., 2012) and the unanticipated, sometimes occurring faster than expected and stretching far into the future. Faster than expected impacts occurred in other cases of Kassam's work, where maps co-generated with the Sami people of NW Russia were immediately used by the Sami to stop a gold mine and ensure tourism was driven from local cultural perspectives [Kassam interview, (Robinson and Kassam, 1998; Kassam, 2009a)]. Iñupiat of Wainwright Alaska, also used a co-generated human-ecological map of marine and land-use to control extraction activities of a major oil company (Kassam and Wainwright-Traditional-Council, 2001; Kassam, 2009a). In the East Africa case, the Maasai team co-developed a land-use map that quickly became a boundary object to learn about and slow down rapid conversion of pastoral and wildlife land into an urban development (Reid et al., 2016b).

As for intangible impacts far into the future, Kassam said:

"The advantage of partnering is the work continues. So you can't anticipate the quantum ways in which the work will affect the future.... To be eligible for funding we need, we need to use the linear language of products, outputs and outcomes. However, in genuine transdisciplinary research where there is humility, trust, and mutual respect, there's this whole universe of the intangible and unanticipated. Of course, some of the unintended consequences may be negative, in which case the participatory approach with a transdisciplinary network is key for articulating an effective and immediate response. Furthermore, a participatory approach ensures a movement of that work beyond the lifetimes of the partners themselves. Increasingly our students come from the very communities we are working with, thus eliminating the divide between them and us. The work takes a life of its own, and it continues, even after the partners have passed on, because it permeates and evolves into different aspects of a community's life."

Of course, any type of impact, especially intangible impacts, are very difficult to measure or attribute to the partnership activities. And yet, the idea of intangible impacts resonated with several of our cases because of the impacts of pastoral leaders and the impacts of the scientists who know how to do collaborative work. It is easy to imagine that the work of pastoral leaders and scientists will ripple out into the future in ever expanding (but also attenuating) rings of influence. Of course, if these leaders create negative impacts, those will also ripple into the future. Here, causal attribution is impossible, but the SWS partnership made a "strong contribution" to this intangible impact.

Are These Outcomes and Impacts Transformative?

It is a big leap to go from describing outcomes and impacts to then describe them as transformative. Let us revisit the definition of transformation from above: the creation of "a fundamentally new system when ecological, economic, or social structures make the existing system untenable" (Walker et al., 2004): 5. While prior empirical work has focused on external drivers of transformation (Olsson et al., 2006), this series of case studies demonstrates outputs, outcomes and impacts that connect to the internal drivers of transformation (Meadows, 1999). We speculate that most co-produced work does not and will not lead to transformation directly, but instead builds institutional entrepreneurs, leads to social innovation, informs society and helps local to national actors to adapt more effectively and be more resilient in the face of change. For these projects to be transformative, there are many factors that would need to align, including external factors (Olsson et al., 2006), enduring social networks, and the power to put new insights into practice.

It is also a matter of discussion whether or not transformation of systems is a desirable goal, even though there are strong calls for transformation in the sustainability science community (Folke et al., 2002; Gunderson and Holling, 2002; Biggs et al., 2010; Westley et al., 2011; O'Brien, 2012; Moore et al., 2014). Obviously, all change, transformational or not, has political aspects and involves trade-offs of costs and benefits for different interest groups.

What makes an outcome and impact transformative? As we saw above, transformations occur when institutional entrepreneurs recognize when windows of opportunity open and know what leverage points and social innovations to use in those windows. Simply, the more fundamental the change caused by a leverage point, the more transformative it is. Fundamental changes are those that change the "underpinning values, goals, and world views of actors" by those who have the power to change the system's structure and institutions and the power to access information about the system (Abson et al., 2017):32. Indeed, these rangeland partnerships aim to make those fundamental changes by changing the paradigms about problems, how to solve them and who solves them. They also change the paradigm of science by shifting the power of expertise away from science alone to all knowledge keepers.

There is some evidence that the process used by some of our cases coincided with the opening of windows of opportunity in national political cycles to allow some of our cases to contribute to major system transformations in policy, which then may have transformed society. In these cases, the co-produced research did not cause society to transform. Instead, the research, at the right time and with the right partners, helped other efforts catalyze and accelerate transformations already underway. This occurred in our East Africa case when development and implementation of a new national constitution in 2013 provided this window of opportunity. Here, the project facilitators and other researchers were asked to participate in task forces to develop the new Wildlife Act associated with the new constitution. The team was able to put into place fundamental changes that now allow pastoral communities to lead and manage community conservancies for the benefit of pastoral livelihoods and wildlife conservation for the first time.

In other cases, the window of opportunity for policy changes was not yet open, and thus the work provides foundational groundwork that may help catalyze and accelerate change in the future. In our Mongolia case, the project assessed the social and ecological outcomes of community-based institutions. And historical work by the leader of the Mongolia case addressed pastoral mobility, land tenure and community response to disaster. The leader and former Mongolian students have brought this knowledge to many policy fora over the last decade, but this has not resulted in a major change in pastoral land policy, probably because the window of opportunity to implement the law has not opened yet.

Capacity building through the partnership experience also transforms participating scientists. The leader of our Spain and Mongolian cases, Fernández-Giménez said, "*For me the relationships that are developed through partnerships are a microcosm of the relationships we need to build in our society to overcome the false divides between academic and community member, between environmentalist and livestock producer, etc. Only through engaging with each other as whole people, building empathy, trust and a shared vision for the future will we address our environment, livelihood and social issues. Because I am an academic, to strengthen the process I go back to how we train the next generation of researchers, conservationists and even producers (if they obtain formal education). Collaboration must* *be part of the curriculum and co-production should become how we do applied research in natural resources and conservation*" (Fernández-Giménez interview).

The importance of transformative learning cannot be overemphasized. "For transformative learning to occur, this disorienting dilemma must invoke a period of reflection for each participant on how these new concepts, mutual dependencies, data, and methodologies fit together, which may lead to a revision of their existing mental models (i.e., critical reflection)…." (Pennington et al., 2013): 570. This type of learning can have far reaching effects, even transforming power structures and regulatory frameworks (Pahl-Wostl, 2009; Moore et al., 2014).

Are These SWS Partnerships Transforming the Way We Do Science?

We think the partnerships described here are also transforming how we do science and its impacts on society. Research that uses more SWS principles are able to leverage more diverse process outputs and have potential to make more change across more impact pathways (Belcher et al., 2019). In addition to having more impact, we suggest that our SWS partnerships are changing the very process of science through co-production and knowledge integration, who is included as part of science and thus the power structure of science. This new science is not driven by the theories and ideas of science alone, rather the problem at hand is the centerpiece on the "learning table" surrounded by the people who most directly face the problem (like pastoralists, ranchers). This evolution in science is most prevalent in practical and problem oriented fields dealing with complex problems like public health, development, and sustainability (Belcher et al., 2019).

CROSS-CASE ANALYSIS AND THE PECULIARITY OF RANGELAND'S PARTNERSHIPS

We can now hypothesize how different biophysical, social-economic and historical partnership characteristics of each case affected the form and performance of each SWS partnership. Our cases differ the most in their country's values of the Human Development Index (**Table 1**). The HDI varies positively with the number of years of education, life expectancy, and per capita income (UNDP, 2019). We hypothesize that pastoralists from cases in medium to low HDI countries (Kenya, Tanzania, Tajikistan and Afghanistan) and where there is an institutional vacuum (many, including Mongolia) have more need to develop local and innovative solutions, to use researchers to access and affect policy, and to implement pastoral development actions. Support for these patterns exist in our data but is not strong. For example, the women pastoralists in Spain had to innovate new institutional relationships in order to access grazing land and other needed resources (Fernández-Giménez et al., 2019c). In the US case, many researchers have access to policy makers, and thus while this connection is not explicit in our description of the CARM case, it still exists. For example, CARM was incorporated into the US National Climate Assessment, Northern Great Plains chapter as an example of climate adaptive management.

In relation to the role of partnership history, these cases strongly rely on pre-existing relationships between the research team (or key team members) and the communities, and the overall research team approach and openness to a different set of goals and methods. This last variable may be more important that either biophysical or social-economic variables.

Also important may be the general area of governance and policy, specifically the relative dominance of different types of land tenure and thus the relative security of pastoral ownership and access to rangelands (**Table 1**). We did not measure this, so our values in **Table 1** are best guesses. Generally, we observe more private land ownership in the CARM, Spain and Kenya cases than in the others. In the Kenyan case, however, private land is often supported by access to large areas of public land, and thus much of the grazing land is not fully secure for pastoral use. In the CARM and Spanish cases, there may be less opportunity for powerful interests to grab land and thus, perhaps, less pastoral need to use research partnerships to help push back on government or corporate power.

We also hypothesize that cases far from centers of power may have stronger partnerships because pastoralists, again, need to use research to empower their voices with central or regional government. This variable was difficult to measure in our cases, since many cases (Kenya, Reto, MOR2, and Spain) worked in multiple locations that varied from remote extensive rangelands to peri-urban rangelands. We also found no obvious differences in our partnership according to the strong differences in rainfall or project area size in **Table 1**.

This chapter is about partnerships, but particularly those in rangelands. Is there anything special about these partnerships in this environment and with pastoral peoples? We think so for two main reasons. First, we think that partnerships may be particularly innovative in pastoral lands because pastoral people and rangelands are so marginalized and thus must make do with what they have at hand. Second, in analyzing our cases, we argued that rangelands with common property regimes and pastoral populations with lower human development indices may also particularly welcome researchers as partners, in an attempt to reduce asymmetries of power with powerful, non-pastoral actors. This notion is supported by the fact that several of our cases in these situations focused on developing research information with communities to bring to national policy makers to encourage those in power to develop more pro-pastoral policies.

RECURRING CHALLENGES AND THE FUTURE

Recurring Challenges

These approaches come with a raft of recurring challenges, dangers and potential negative pathways. For example, as mentioned above (Chambers et al., in review), found that those cases that focused on how knowledge is produced during co-production did this at the expense of other outcomes. To achieve outcomes, there needs to be full engagement in the action part of the adaptive learning cycle in **Figure 2**.

Participants in our cases saw a whole range of additional challenges. Many were things "we wished we knew at the start" which are recommendations to others taking these approaches. Wilmer, who participated in the Colorado case study said: "*I would advise a new team to engage in team science and transdisciplinary science, engage with the literature, go through a process to think carefully about the lessons already learned and how you will evaluate your work.*"

One of the most difficult challenges is wrestling with who to include and who to leave out in these partnerships. It is important that the initial team does not include only people already familiar to the partnership's leaders (Wilmer interview). Careful thought should be given to the level of power that the participants have in their home institutions' hierarchy, so that there is some prospect of accessing the levers of power (Wilmer, Reid interviews). In other cases, partnerships may want to avoid inviting participants who have too much power, usually from government, so that these actors do not inadvertently disempower marginalized pastoralists (Kassam, Reid interviews).

These partnerships are also complex and require significant time commitments. As seen in **Figure 3**, moving from interdisciplinary (inner ring), to transdisciplinary (middle ring) to transformative (outer ring) science involves more and more complexity and time. It is also operationally complex. Wilmer said, "*We struggle with the complexity of this project. There is a clear need for project coordinators in this work, everyone else has to fill multiple roles over time. Need doers and thinkers and dreamers, need a well-balanced team. For the leaders, it has to be OK not to know stuff.*" And time is always in short supply among participants, so it helps if they are proud of their role and if participants have aligned incentives, values and interests (Wilmer interview). Time availability is an issue also in terms of project and partnership setting. Usual funding for research projects, at least in Europe, is 2–4 years, which is usually not sufficient to fully implement an adaptive co-generation arena for this work.

There is also hidden bias and naivete on the part of participating scientists. When working in many former or current lands of Indigenous peoples in many parts of the world, there is an underlying history of colonialism and often cultural genocide. Biophysical scientists, in particular, tend to ignore or be ignorant of this history. It then becomes incumbent on team members who are Indigenous Peoples or community members, or those trained in social science or the humanities to explain the situation to the biophysical scientists and explain why certain actions, questions or practices will trigger the pain of this history for community members (Kassam interview). In addition, biophysical scientists often think they are entirely neutral about the subjects they are working on, which they are not. For example, Wilmer from the Colorado team said, "*We self-facilitate, so we made a rule that the scientist involved in an issue is not allowed to facilitate discussion that they feel passionate about*." Social scientists have biases too. For example, their models of social relationships may not be backed by data and may be wrong (Wilmer interview).

Moreover, interdisciplinary scientists still do not have an easy fit within traditional academic systems in many countries (e.g., Spain). Early career researchers who are pursuing such pathways (very frequently women) require extra-training and experience to navigate between disciplines, knowledge systems and languages, and face precariousness for years while struggling to find a place in natural sciences or humanities departments, which hinders their involvement in SWS processes.

There is also a real potential that partnerships can results in unintended negative outcomes. If a co-production process strengthens oppressive power structures, the process will likely hurt local participants (Wilmer interview). Scientists have to be ready for decision makers to cherry pick their results and make decisions on single facts that are not supported by the general conclusions of their study. For example, a large modeling study in Tanzania showed that human population growth and expansion of small maize fields in a multiple use conservation area had little overall impact on wildlife populations. But one line in the report described what could happen if the cropland expanded dramatically. This one line was used by political appointees to justify putting a moratorium on crop cultivation by any pastoral family in the conservation area (Reid interview).

Finally, there just is not enough evaluation of these SWS partnerships (Wiek et al., 2014; Belcher et al., 2019). Wilmer said, "*There is a whole science of evaluation for doing this efficiently and effectively. There are many, many different methods and approaches. In our case, self-reflection has been very valuable.* Fernandez-Gimenez said, '*It's not yet clear to me what impacts, if any, can be traced directly to our partnership approach in this project, (but it did lead to)… several of the women pastoralists ….participating in a high-level side event at COP 25* (the UN Framework Convention on Climate Change in Madrid in 2019)."

The Future: Transformative Science With Society

As the Models of Science Change, What Is SWS Research Then Becoming?

It is becoming research that challenges most of our conventional wisdom about how science should be done, is entirely redefining the boundaries of science, leads to unexpected insights into how to do science and how to have impact on the world's most challenging problems with science. It is also more than this. It turns out that this is exactly how the US National Science Foundation (NSF) defines "transformative science," but their only examples have to do with cutting edge scientific discovery. Science with society and transdisciplinary research are evolving into a form of transformative science that is much beyond what NSF is now describing because it requires full engagement and innovation with society, which calls on scientists to deal with much more complexity than when they work alone on a problem. If NSF's transformative science definition is describing "hard science" discovery, then science with society is "difficult and complex science" discovery.

Science with society is now rapidly evolving into a new type of science as demonstrated by our SWS partnerships in rangelands. We call this *transformative science with society* and it has at least the following features.

We think there are a number key changes that need to occur in this transformation of science. First, as described above, there is a need to move this type of work so that action and science are on equal footing. Our rangelands partnerships demonstrate different approaches to doing this from experimenting with management practices in Colorado to including people who pursue action as part of the core team (community and policy facilitators, East Africa). The next evolution, already taking place, is leadership and agenda setting of SWS teams by pastoralists or conservation practitioners or government managers. In many cases, research may not be part of these partnerships initially, brought in later to evaluate a process, even though this is not ideal.

A second systems transformations needed in western science are efforts to *decolonize how western science is done*, so it is more inclusive of and driven by non-western ways of inquiry and knowing, especially in the area of the environment. Key here is drawing on Indigenous science and resource management models (Pickering Sherman and Sherman, 2010) and decolonizing western scientific methodologies (Smith, 2002). This also means breaking down the cultural myth of pristine landscapes in conservation, for example (Gilio-Whitaker, 2019). True decolonization, in countries settled by colonists, has to reach deep enough to address the issue of land, power and privilege, and whose worldviews "get to count" as knowledge and research (Tuck and Yang, 2012). It also means addressing power inequities in western science and conservation (Willow, 2015).

Thirdly, there needs to be more *focus on power* and its role in SWS partnerships**.** Many scholars and practitioners recognize that this approach needs to give more attention to power (Brandt et al., 2013; Cornell et al., 2013; Schuttenberg and Guth, 2015; Miller and Wyborn, 2018; Knapp et al., 2019). This means understanding "how power is used, expressed and practiced" (Knapp et al., 2019):8. This starts with navigating the power between team members within science, within practice and also between science and practice. It also involves considering who leads the SWS partnership and how knowledge is integrated (Knapp et al., 2019). It also means understanding who has the power to make change at what level of scale. Knapp et al. (2019) found that approaches that focus more on action pay more attention to power and power sharing is greater in projects that focus on the local rather than broader scales.

If this science is to be transformative, it needs more focus on *systems transformations science*. As described above, much new focus is on how systems transform. Key here is when institutional entrepreneurs recognize the opening of windows of opportunity and if they know what leverage points and social innovations to use in those windows. This approach is in its infancy, but will strongly inform this evolution in SWS research, allowing targeted action to transform systems. None of our cases explicitly used transformations science in their work.

Another need is more focus on the *moral/ethical aspects* of this work. The scholarship of these partnerships is replete with moral statements about societal change, justice, inclusion and equitability. We expect these aspects to be more prominent in this work in the future.

Also, we all need to become students of *knowledges, epistemology and mental models*. Our Colorado case highlights the importance of epistemology and mental models (Fernández-Giménez et al., 2019b). We expect that this foundational insight will become even more important in future work. All of our cases changed mental models of participants, but only a few recorded and evaluated these changes.

Transformative learning is clearly at the core of this approach to science**.** It is also clear that social and particularly transformative, *triple loop learning is foundational* to this new evolution of SWS research. The focus will likely be on how changes in participant's (including researcher's) understanding of themselves occur, how they revise their belief systems and how they change their behaviors [e.g., (Mezirow, 1991)].

We can also see the need for more focus on intangible and long-term impacts and their evaluation. It is clear in our cases that *long-term engagement* through a SWS partnership is the foundation of long-term (and sometimes intangible) impacts. These partnership just don't fit a short-term "project" model very well. Those partnerships that extend into the future should continue to yield more lessons about impacts, but only if they are rigorously evaluated against achievement of both tangible and intangible outcomes.

Finally, critical self-assessment, which addresses the different and differential social positions, power and epistemologies of participants, is needed in all collaborative partnerships. And, as described above, the future of this science needs better evaluation and, perhaps, may achieve more solid attribution. This will also improve research design and implementation (Belcher et al., 2019). Chief hurdles in this evaluation is the complexity of the multiple impact pathways of this work and the difficulty of identifying a "counterfactual comparator." Belcher et al. (2019) suggest the best approach is theory-based evaluation, using tools like a theory of change. In our cases, some employed robust reflective evaluations on team process and also as part of training sessions.

Finally, all of our interviewees recognized the difficulty and challenges in doing this work. And yet, they all are deeply invested in continuing this approach, partly because it has a deep moral aspect to its process. Clearly, science as a process has deep cultural elements, some that are inclusive and some that are less inclusive. The teams here are on a discovery pathway to magnify the inclusive nature of science and learning together.

AUTHOR CONTRIBUTIONS

RR led the interviews & data analysis. RR, MF-G, HW, TP, K-AK, LMP, JD, KJ, CJ, TU, EO-R, FR, and CK wrote the paper. RR, MF-G, HW, TP, K-AK, and LMP participated in interviews. RR, MF-G, TP, K-AK, JD, DN, EO-R, FR, and CK led a partnership team. RR, HW, LMP, KJ, CJ, TU, DK, and AY participated on a partnership team. All authors contributed to the article and approved the submitted version.

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Multi-Scape Interventions to Match Spatial Scales of Demand and Supply of Ecosystem Services

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The original focus on supply of ecosystem services is shifting toward matching supply and demand. This new focus underlines the need to consider not only the amount of ecosystem services but also their spatial and temporal distributions relative to demand. Ecosystem functions and services have characteristic or salient scales that are defined by the scales at which the producing organisms or communities exist and function. Provision of ecosystem services (ES) and functions can be managed optimally by controlling the spatio-temporal distribution of landscape and community components. A simple model represents distributions of ES as kernels centered at the location of interventions such as grassland restoration or establishment of nesting habitat for pollinators. Distribution kernels allow non-habitat patches to receive ecosystem services from species they cannot support. Simulations for three contrasting ES producing organisms (bumblebees, Northern Harriers, and oak trees) show the effects of interacting distribution of interventions and demand for ES. More ES demand is met when the intervention is spread out in the landscape and demand is evenly distributed, particularly when the kernel radius is much larger than the minimum intervention required for the ES producing unit to be established. Because different functions have different reaches and saturation points, the level of ES demand met at any point in space can be modulated by controlling the spatial distribution of landscape components created by interventions. Different ES can be promoted by the same type and quantity of intervention by controlling the continuum of scales in the distribution of interventions. This work provides a conceptual and quantitative basis to consider the spatial design of interventions to match ES supply and demand.

Keywords: ecological field, landscape structure, restoration, ecosystem function, spatial kernel

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INTRODUCTION

Ecosystem functions and services have characteristic or salient scales at which they operate, which are basically defined by the scales at which the organisms associated with the service operate (Liu et al., 2017). Ecosystem services (ES) are supplied by functions and associated organisms in the habitat or land type they occupy, and they are demanded and consumed by humans. Production of ES depends on the amount of suitable land and density and distribution of corresponding organisms in these lands. The degree to which demand is met depends not only on rate of production but also on the movement and distribution of

ES beyond the location where they are produced, which requires flow paths and may include sinks (Bagstad et al., 2013).

The full value of ecosystem services can be realized only when supply and demand are connected by suitable distances and processes. Until recently, most ES studies focused on potential production and supply, neglecting the demand side of the system (Sala et al., 2017). Syrbe and Grunewald (2017) define six spatial relationships between supply and demand: "local," when supply and demand are in the same area; "proximity," when they are connected by natural transfer from a service producing area to an adjacent service benefitting areas; "process," when natural processes transfer services across "service connecting areas" that separate producing and benefitting areas; "access," when beneficiaries travel to the producing area to enjoy the service; "commodity," when actors who share in the benefit collect and deliver the goods to beneficiary consumers; and "global," when the services are naturally distributed to the whole planet and cannot be spatially restricted. Because it is categorical, this classification may be easier to use for regulation and planning than the continuity of distances and arrangements that can be addressed by the framework proposed by Bagstad et al. (2013).

Bagstad et al. (2013) provided a comprehensive basis to evaluate the production and use of ecosystem services that pivots on the idea that areas can be classified as sources, sinks, rival-use and non-rival use of services. Different areas are connected by carriers of ES. User areas may receive more or less of the ES depending on the carrier flow routing because it determines a decay of service with distance and the carrier may be depleted by intervening sinks or rival-use areas. For example, the aesthetic and recreational value of green space decline with distance because beneficiaries have to travel to the source location, which is costly.

Open, green space can be a source (or service providing areas) of multiple ES, including the crucial supply of recreation and opportunity for healthy development. In an epidemiological study involving about 1 million people of Denmark, Engemann et al. (2019) found a strong association between availability of green space within ∼210 m of the home during childhood and reduced risk of a wide spectrum of psychiatric disorders later in life, even after correcting for level of urbanization, socioeconomic factors, parental history of mental illness and parental age. Risk of mental disorders and availability of green space exhibited a dose-response relationship. Grasslands and rangelands provide green and open spaces with aesthetic and recreation value, in addition to multiple other ecosystem services (Yahdjian et al., 2015), but those services must reach demand in order to become realized. The characteristics of their spatial distribution is critical.

Spatial distribution of ES demand and supply can be controlled by different factors at different scales. Liu et al. (2017) found that ecosystem service distribution (water purification, water supply, soil retention, and crop production) was controlled by human activities at a scale of 12 km and by abiotic factors at a scale of 83 km in the highly developed and densely populated Taihu Lake Basin in China. For example, grasslands and grazing lands are sources of forage and recycle animal excretions. When animals graze directly at pasture in moderate densities, the spatial distribution of supply and demand at the farm scale can be naturally matched by proper management. However, when animals are concentrated in certain regions, spatial distributions of demand and supply at regional scale become disjoint and can cause environmental damage (Syrbe and Grunewald, 2017), both by requiring transportation based on fossil fuels or by contamination of water. Forage produced that is not directly grazed by livestock can be harvested and becomes a commodity whose benefits can be widely distributed through regular market carriers. Animal waste is increasingly becoming a similar commodity used for fertilization and composting. Because of transportation and handling costs, the net value of the services declines gradually with distance to the user. However, the market for animal waste is much less developed than the hay market, so the value of waste recycling services declines more abruptly with distance.

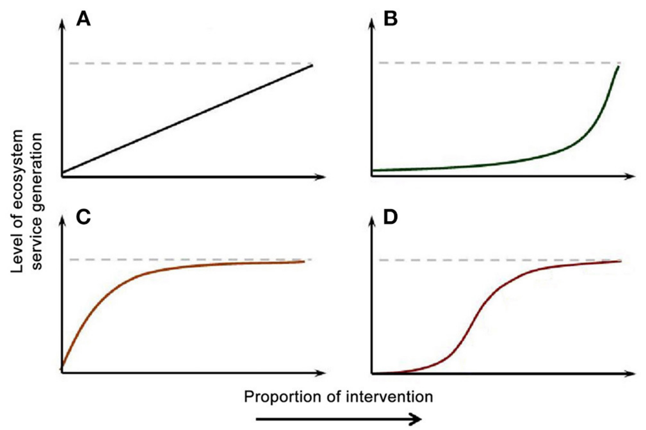

FIGURE 1 | Types of relationships between proportion of area receiving an intervention such as planting of hedgerows or flower strips and level of production of ecosystem services. **(A)** Linearly increasing ES with intervention proportion. **(B)** ES that has an ecological threshold to be produced, for example, one that is produced by a species that needs a certain amount of habitat to establish. **(C)** Rapid saturation of ES production because limiting factors other than intervention. **(D)** Sigmoid relationship resulting when mechanisms for **(B)** and **(C)** take place within the range of proportion of area receiving the intervention. From Lindborg et al. (2017); used under the Creative Commons Attribution License.

Production of ES in agricultural landscapes likely depends on the extent of interventions. Lindborg et al. (2017) considered the effects of amount and extent of interventions such as planting hedgerows on the level of ES produced. They proposed four types of responses of ES production to amount of intervention expressed as a proportion of the area where ES are considered (**Figure 1**). The theory suggests that the same interventions have different effects on ecosystem services that differ in mobility, but also that the same ES responds differently depending on intervention scale. For example, when the extent of the landscape is small, even a large proportion of area devoted to intervention may create limited or no ES if the ES is based on the establishment of a population or community that has a minimum area requirement.

The goal of my present work is to further develop the idea that scale affects ES by considering not only extent, but the continuum of spatial distribution characteristics, and by including the interaction with spatial distribution of demand. I consider proportion of ES demand met as a function of type, amount and spatial distribution of intervention with a simple but effective quantitative model and illustrate the effects with examples.

MODELING FRAMEWORK

I created a static, deterministic model of ecosystem service (ES) supply and demand over space to illustrate the relationship between the proportion of the landscape that receives an intervention and the proportion of ES demand that is met. For simplicity and to prevent errors in the computation of spatial integrals, the model represents space in a single dimension, over a line. Results are quantitatively correct for areas if proportions of lengths are translated into equal proportions of area, instead of squaring them.

First, I describe the components of the model and then I describe simulated examples. Examples use realistic parameter values for three types of ES and organisms that have contrasting characteristics, to explore the impacts of amount and distribution of interventions such as restoration or habitat creation on the quantity of ES demand that is met. The context is a landscape with a patchwork of agriculture, pastures, grasslands, hedgerows and trees where interventions such as habitat creation or reforestation are considered to supply specific ES demanded in the landscape. I selected three examples (carbon sequestration and soil OM provided by oaks, pollination services provided by bumblebees and predation services provided by Northern Harriers) of ecosystem services classified as biotic regulation and maintenance services to show contrasting ratios of minimum intervention size necessary (the "exclusion radius") and size of the area supplied with ES (kernel radius). The fact that I could provide realistic and understandable simulations with parameters based on published articles also affected my choice of organisms and services.

Ecosystem Service Supply and Demand

Supply

Ecosystem services are provided by functional units (FU) such as individual animals, plants, communities or colonies. Each functional unit requires a certain amount of landscape area treated with an intervention such as a certain type of vegetation that provides nesting habitat and cover in order to exist sustainably. Once a unit occupies its required space, no other FUs of the same kind can occupy it. In the model, the size of the minimum intervention required and preempted by each FU is represented by a radius r_{min} that is unit specific. Because each FU "uses up" the intervention within r_{min}, I also refer to it as "exclusion radius," because no other FU of the same kind can use the same space to establish. Each FU provides one unit of ES that is distributed over space according to a kernel that typically decreases with increasing distance to the center of the intervention. For the cases depicted here, I chose a triweight kernel (Equation 1) as a generic example that can be scaled easily and has finite support. Its single parameter λ is the reciprocal of the radius or extent of the kernel r_k. The kernel has value *K(u)* when *u*, the absolute distance to the center of the kernel, is $<1/\lambda = r_k$, and 0 everywhere else. Kernels are specific for the FU and the function or ES under consideration.

$$K(u) = \lambda \,\frac{35}{32}\, \left(1-\lambda^2 u^2\right)^3 \qquad (1)$$

$$support:\ |u| \leq \frac{1}{\lambda}$$

The framework that I propose can be used with any kernel desired to study the impacts of amount and distribution of specific functional units on the total amount of services realized. I expect that results will differ depending on the type of kernel used. Although I use realistic examples, the model is for specific illustration of general principles. A practical application of the framework would require modeling kernels based on data.

The distribution of supply kernels is controlled by the spatial distribution of the intervention. I consider two extremes, a compact distribution where the intervention is a single patch in the center of the landscape and a uniform patchy distribution where the intervention is spread out into equidistant patches of size equal to the minimum required by each FU. The total amount of ES supply per unit distance at any point x in space, *S(x)* depends on how FUs interact when their kernels overlap. I represent two extremes of a continuum: (1) independent, when the supply at any point is the sum of all kernels (Equation 2), and (2) exclusive, when the supply at any point is the maximum of all kernels (Equation 3). An example of the former would be predation services by organisms that do not interact or keep territories; the total amount of hunting time at a point is the sum of the hunting time of all individuals whose home ranges overlap at a point. An example of the latter would be a case where there is exclusive territoriality of hunting ranges.

$$independent:\ S(x) = \sum_{i=1}^{i=n} K(x-x_{0i}) \qquad (2)$$

$$exclusive:\ S(x) = \max{}_i\, K(x-x_{0i}) \qquad (3)$$

$$x_{0i}: centers\ of\ kernels$$

Demand

I explore two distributions of demand, *D(x)*, constant across the landscape and uniformly distributed patches. These distributions represent interesting cases that can represent realistic situations. For example, pollination services in landscapes dominated by vegetable crops and fruit trees have a spatially continuous demand for pollination by bumblebees, whereas landscapes where pastures and vegetables or fruit trees are interspersed represent the patchy distribution. Patchy demand is represented by the total demand in the landscape divided into *n* equidistant patches, each with length equal to *1/(2n) * landscape length*. This doubles the demand density within patches relative to the average for the landscape.

Demand and supply of ES have units of *ES-unit* $length^{-1}$ $time^{-1}$, where *ES-unit* is specific for each ES. Because units differ between services, comparison between different services requires the removal of dimensions. This is achieved by scaling demand as a fraction of the maximum of the kernel and by expressing amounts of ES demand met as percentages of the total demand present in the landscape. I explore three values of average ES demand per unit landscape length, 1, ½ and ¼ of the maximum value of K, which is $K(0)$.

Demand Met

In summary, the model framework includes (1) a spatial distribution of ES demand (constant or patches) across a landscape where (2) various amounts of an intervention are applied in a compact or spread out patchy distribution, with (3) ES producing FUs with specific kernel scale (r_k) and minimum intervention radius requirements (r_{min}) established in the intervention. Locations with the intervention are occupied by FUs, each of which requires and preempts a fixed amount (2 r_{min}) of intervention and supplies ES according to the kernel. Finally, the amount of demand met or "realized" is the spatial integral of the minimum of supply and demand at each point in the landscape (Equation 4, where L is the size of the landscape).

$$T_{ES} = \int_0^L \min\{D(x), S(x)\}\, dx \qquad (4)$$

The metric I used to describe the effectiveness of interventions is the percentage of the total demand that is met (Equation 5).

$$Y = 100\ T_{ES} / \int_0^L D(x)\ dx \qquad (5)$$

Oak Restoration for Carbon Sequestration and Soil Improvement

First, consider the effects of woody plants on savanna soils. Oaks are keystone species in Mediterranean-climate oak savannas that occupy 4 million ha in California and 3 million ha in southeast Europe (Marañón et al., 2009). Other oak savannas used to occupy vast areas between eastern deciduous forests in the east and grasslands in the west of the US, but <1% remain today (Brudvig and Asbjornsen, 2008). Both types of ecosystems are of conservation concern. Several species of oaks, particularly Blue (*Quercus douglasii*) and Valley (*Quercus lobata*) oaks are key components of the oak savannas in California. These trees provide habitat and multiple functions to the ecosystem (Dahlgren et al., 2003). Soil organic carbon and cation exchange capacity are greater, and soil bulk density is lower, under Blue oak canopy than in the surrounding grassland (Frost and Edinger, 1991). A similar type of spatial provision of soil services is observed in other places such as semi-arid Kenyan savannas (Belsky et al., 1989) and semiarid rangelands in the US (Gill and Burke, 1999). I consider the effects of trees on soil properties and soil quality, which the trees change significantly by adding large quantities of litter and roots that end up enriching soil organic matter and improving multiple soil functions including supply and cycling of nutrients, infiltration and water holding capacity. Organic matter addition happens mostly within the perimeter of the canopy and moves very little horizontally. No other trees grow under the canopy until the "mother" tree dies and leaves a gap. I simulate the effects of planting oak trees that reach a canopy radii (r_{min}) of 0.0225 or 0.0425 hm and kernel radius of 0.025 or 0.045 hm (**Figure 2A**). This represents an ES with a low r_k:r_{min} ratio ranging from 0.59 to 2. The case where the exclusion distance is larger than the kernel is considered as a possibility, for example for an ES that responds in a strongly non-linear manner to soil organic carbon content, with a threshold that is only achieved well inside the canopy radius. Average demand is set to 43.75, 43.75/2, or 43.75/4 ES units per hm.

Northern Harrier Nesting Habitat in Integrated Grazing-Cropping Landscapes

Second, consider predation services provided by Northern (and Hen) Harriers (*Circus hudsonius* and *Circus cyaneus*). Northern Harriers are the only North American Harrier and although they are declining due to habitat loss, they still range in the whole section of North America NW of a line from Baja California to Halifax. These birds require nesting habitat consisting of meadows, wetlands and grasslands with low thick vegetation, and they hunt in widely open fields feeding mostly on voles, rats and other rodents. A few ha of lightly grazed grasslands may provide such habitat, particularly if patches are protected from grazing (Dechant et al., 2002). The intervention to promote this ES is the creation and protection of grassland patches with perching sites and undisturbed by grazing, tillage domestic animals or humans. Once a pair of birds establishes a nest, it defends and hunts in a territory that can range from 10 to 300 ha depending on the amount and quality of hunting habitat. Individuals can fly up to 100 km in a day and hunting territories can overlap depending on prey density (Massey et al., 2009). I explored two habitat radii ($r_{min} = 1.5$ and 2.5 hm) and two kernel radii ($r_k =$ 2.5 and 5.0 hm) commensurate with literature values (**Figure 2B**). This represents an ES with an intermediate kernel/exclusion ratio ranging from 1 to 3.33. Average demand is set at 0.4375, 0.4375/2, or 0.4375/4 ES units per hectometer.

Bumblebee Colony and Habitat for Pollination Services

Last, consider pollination services provided by native eusocial bumblebees. Bumblebees (e.g., *Bombus*) are an important component of the pollinator guild that is threatened by lack of forage, land use change, parasites and diseases (Samuelson et al., 2018). These species are annual social species that grow in colonies by first having a stage with cohorts of workers and then switching to producing queens and males that disperse while the remaining workers and queen survive (Crone and Williams, 2016). These bees require nesting habitat without tillage or mowing where there is grass and dead plant material providing cavities such as old bird and rodent nests. Bees do not defend territories, and each nest requires just a few square meters of habitat with protection from predators. The intervention can be thought of as the creation of patches or protective vegetation and nectar rich flowers where we place nest boxes with starter bee colonies. Each colony can grow to have 50–500 workers that feed up to 2 km from the nest, but most activity is within a few

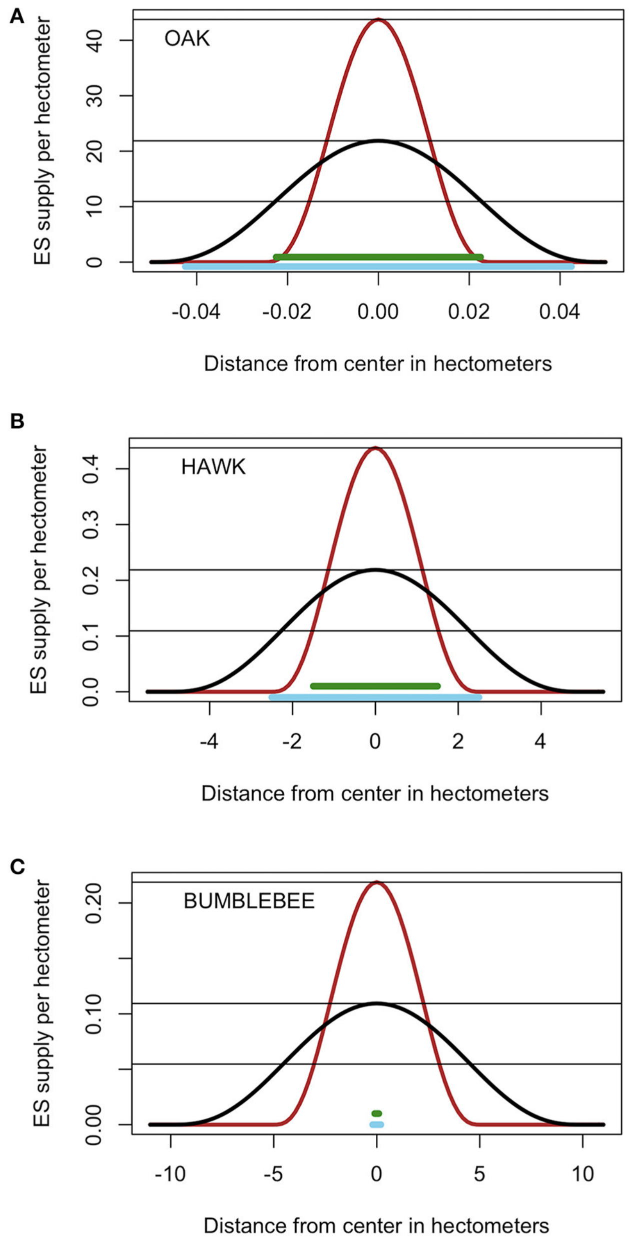

FIGURE 2 | Characteristics of the kernels and minimum intervention areas required and preempted by ES producing functional units. Two plausible kernel radii and two sizes of required intervention area are considered for each species. **(A)** Oaks, **(B)** Northern Harriers, **(C)** bumblebees. Black and burgundy lines represent the two kernels or proportion of one unit of ecosystem service per unit length as a function of distance to center. Thick horizontal green and blue lines represent the two amounts of landscape needed and preempted by each unit. Thin horizontal lines represent the three levels of average ES demand per unit landscape. Functional units are one tree for oaks, one nesting pair for Northern Harriers and one colony for bumblebees. Note the difference in the scales of the vertical and horizonal axes.

hundred m (Thomson, 2004; Goulson, 2010). Two minimum habitat radii (r_{min} = 0.1 and 0.2 hm) and two kernel radii (r_k = 5 and 10 hm) were simulated (**Figure 2C**). This represents a FU with an extremely high ratio of kernel to minimum radius (r_k:r_{min}) ranging from 25 to 100.

RESULTS

Percentage of demand met increased with increasing proportion of the landscape represented by the intervention, and the slope decreased with increasing landscape demand (**Figures 3–5**). In all cases simulated, percentage of demand met increases in a stair-step fashion where the steps represent the amount of intervention required for one additional ES producing unit to be established. Steps are not clearly visible in some graphs because they are small relative to the graph resolution. The lowest proportion of demand was met in the oak restoration with the highest demand, when the kernel radius and the minimum intervention radius r_{min} were similar (**Figure 3L**). Conversely, 100% of the demand for bumblebee pollination services was achieved with 2.5% of the landscape used for nesting and cover, when kernel radius (10 hm) was 100 times the minimum intervention radius and demand was just ¼ of the kernel maximum, *K(0)* (**Figure 5G**).

In general, more ES demand was met when the intervention was spread out in the landscape (blue lines) than when it was in a single compact block (red lines). However, there were significant high-order interactions among all factors. The advantage of spread out over compact intervention distribution decreased as the exclusion radius increased and increased with increasing kernel radius within ES type (soil improvement by oaks, population regulation by Northern Harriers or pollination by bumblebee). The size of this 2-way interaction depended on the level of demand. For interventions with exclusion radius commensurate with the ES kernel radius (**Figures 3A–C,J–L, 4D–F**), the advantage of spreading the intervention was nil.

Both for oaks and Northern Harriers, the proportion of demand met at any level of intervention declined as average demand per unit landscape increased. This is a consequence of the low kernel:exclusion ratio, which prevents the "stacking" of service supply from many centers. When demand of ES per unit landscape is high relative to the kernel scale, it is impossible to meet a large proportion of the demand unless services provided by different units are additive and units can be packed densely enough. The maximum packing density is limited by the exclusion distance or amount of landscape that is preempted by each unit. In the case of bumblebees, the packing is not limited because multiple colonies can be established close to each other relative to the reach of their supply kernel.

Considering all results together, the most dramatic differences appear among species, although all three examples fall under the class of "ES proximity" defined by Syrbe and Grunewald (2017). On one extreme, oak restoration effects on soil organic matter are limited -relative to the maximum achieved at the tree center- because the benefits do not extend much beyond the tree canopy, and canopy overlap is not allowed. These conditions practically eliminate the effects of tree spatial distribution on the total demand met. On the other extreme, establishment of bumblebee colonies evenly spread in the landscape saturate the demand with very small proportions of landscape used for the colonies.

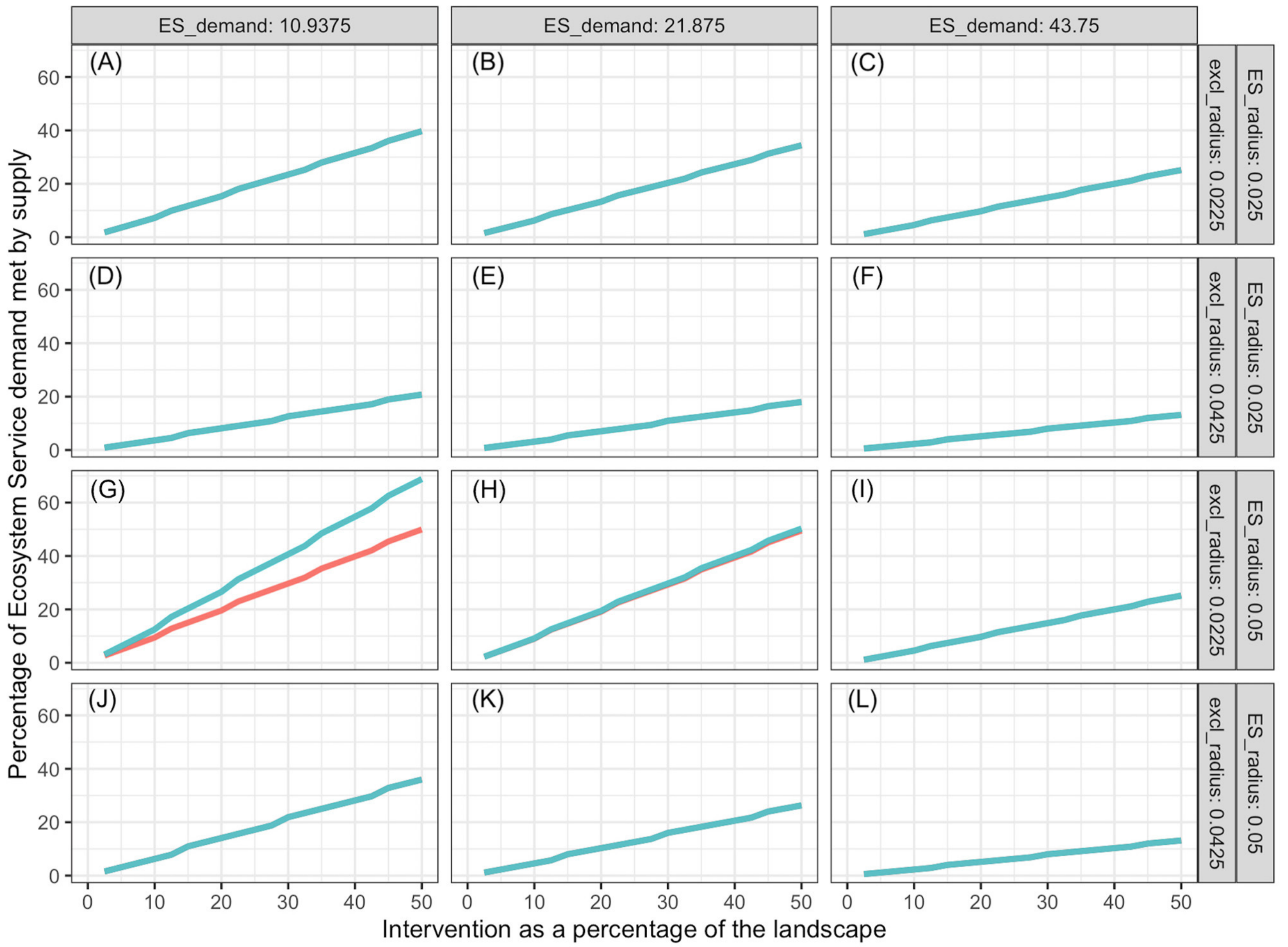

FIGURE 3 | Soil organic matter and quality services provided by oaks as a function of proportion of landscape that receives intervention, ES demand (columns), supply kernel (r_k), and exclusion (r_{min}) radii (rows), and distribution of interventions. Intervention consist of planting oaks. Blue lines represent interventions spread out evenly over the landscape; red lines represent interventions in a compact area in the center of the landscape. Except for **(G)**, the red lines are behind the blue lines. Labels **(A–L)** refer to the combinations of ES demand, supply kernel radius and exclusion radius indicated on the columns and rows of the figure grid.

Each new colony preempts a very small fraction of landscape but extends services over a large distance. When colonies are packed in a compact central intervention patch, the proportion of demand met increases linearly with proportion of landscape under intervention, and the slope is only slightly affected by other factors.

Proportion of demand met tended to decrease when the distribution of demand is concentrated in patches instead of being uniformly spread (not shown in figures). This effect happens because a concentrated demand is more likely to exceed local supply, and therefore it is stronger when kernel distance is limited by long exclusion distances, and when spatial exclusion prevents the stacking of kernels.

If interactions among ES supplying units (nesting pair of Northern Harriers, bee colonies, individual trees) are highly interferential and limit the total supply at any point to be that supplied by a single unit (Equation 3), proportion of demand met is reduced, particularly when demand per area is high relative to the maximum that a single unit can provide (**Figure 6**). For example, when "local" bumblebees prevent members of other colonies from foraging in the territory near the "local" colony, and demand per area is twice the maximum a colony can provide, a maximum of 50% of the demand would be met (**Figure 6C**). The negative effects of exclusive territory use beyond the minimum intervention area needed per FU (r_{min}) declines to almost nothing when the ratio of kernel to r_{min} declines to 3 or less. Highly territorial organisms with territories much larger than the minimum intervention needed for establishment (r_{min}) are inefficient ES providers unless demand density is much lower than what each FU can provide.

DISCUSSION

A model of supply and demand of ecosystem services that takes into account the distribution of services around the central locations of ES producing units shows that the efficiency with which ES demand is met depends strongly on the spatial distribution of the units and the relationship between the size

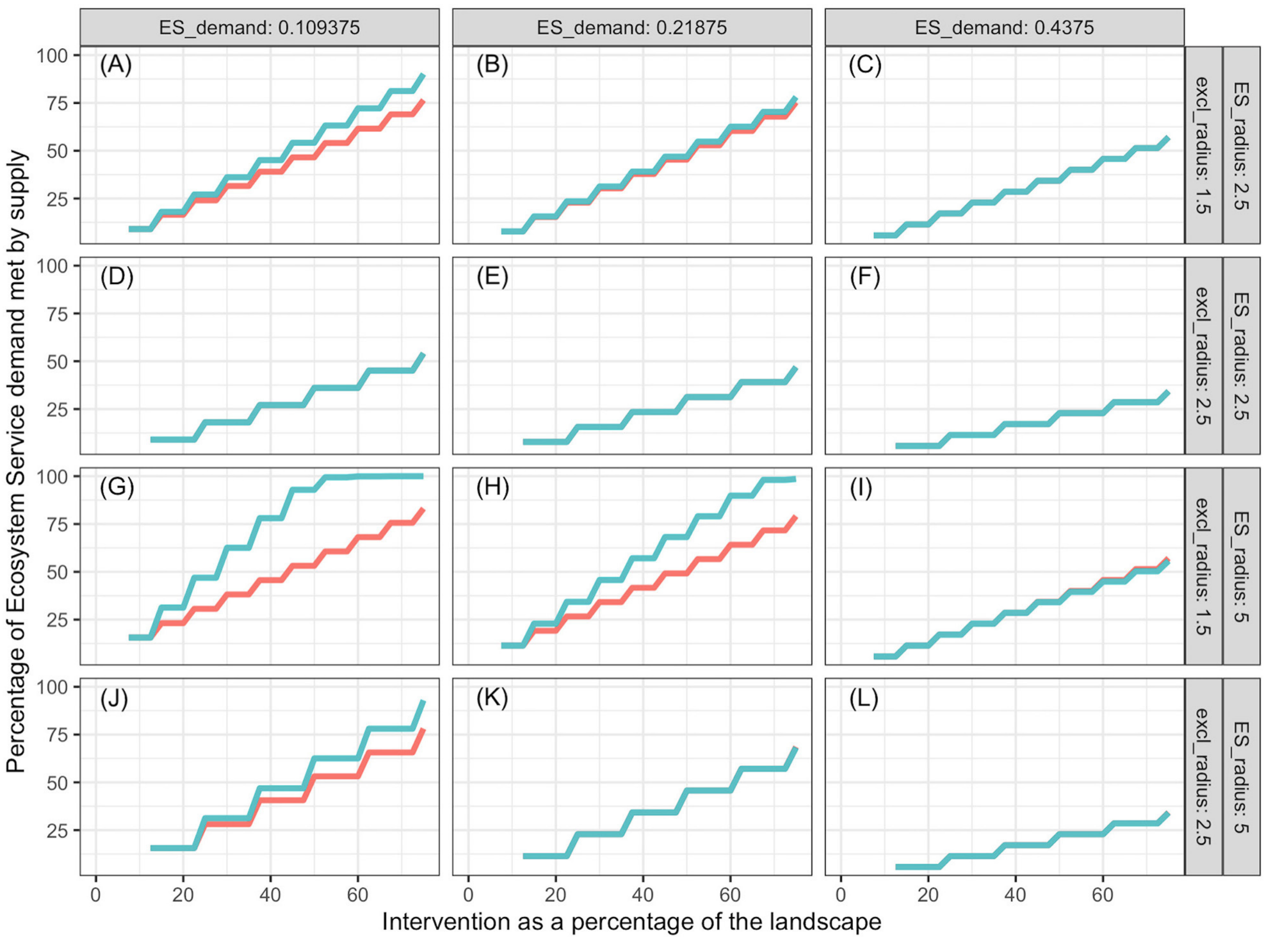

FIGURE 4 | Predation services provided by Northern Harriers as a function of proportion of landscape that receives intervention, ES demand (columns), supply kernel radius and exclusion radius (rows), and distribution of intervention. The intervention is the creation of nesting habitat with tall bunchgrasses and perching sites that are undisturbed by human or domestic animal activity. Blue lines represent interventions spread out evenly over the landscape; red lines represent the case when the intervention is performed as a compact area in the center of the landscape. Some blue lines cover the red lines. Labels **(A–L)** refer to the combinations of ES demand, supply kernel radius and exclusion radius indicated on the columns and rows of the figure grid.

of service producing area and service benefitting area, which is inherent to the service and the specific organism, population or community providing the service. This modeling framework borrows heavily from ecological field theory (Walker et al., 1989) whereby plant interactions are represented by the overlap of individual domains of influence. Field intensity declines with distance from the plant center according to various response types. In the simulations I present, the ecosystem service kernel represents the ecological field and the exclusion radius represents the actual space occupied or preempted by the plant or other ES producing unit.

Ecological functions or effects that decline with distance to a central place in a kernel-like fashion have been described for many organisms. I think that effects that decline with distance are a result of the fact that effects must involve flows of matter, energy, or information (which actually is in energy or matter) (Cadenasso et al., 2003), and resistance to flows, signal degradation and dilution increase with distance. Effects that do not decline quasi-exponentially with increasing distance require specific processes and inputs of energy to reverse the tendency. For example, (1) concentrations of soil organic matter and extractable nutrients decline, and soil temperatures increase in a curvilinear fashion with increasing distance to the trunk of *Acacia tortilis* trees in a Kenyan savanna (Belsky et al., 1989); (2) seed dispersal depends on height of seed release and declines steeply with distance to mother plant (Davies and Sheley, 2007); (3) vole herbivory damage to tree seedlings declines with increasing distance to forest edge (Cadenasso and Pickett, 2000); (4) centrifugal (or centripetal, depending on species) redistribution of rainfall by tree canopies increases with distance to the tree (Frischbier and Wagner, 2015).

The model is applied to three specific examples of ecosystem services, but how general is the approach? The three examples (carbon sequestration and soil OM provided by oaks, pollination services provided by bumblebees and predation services provided by Northern Harriers) are biotic regulation and

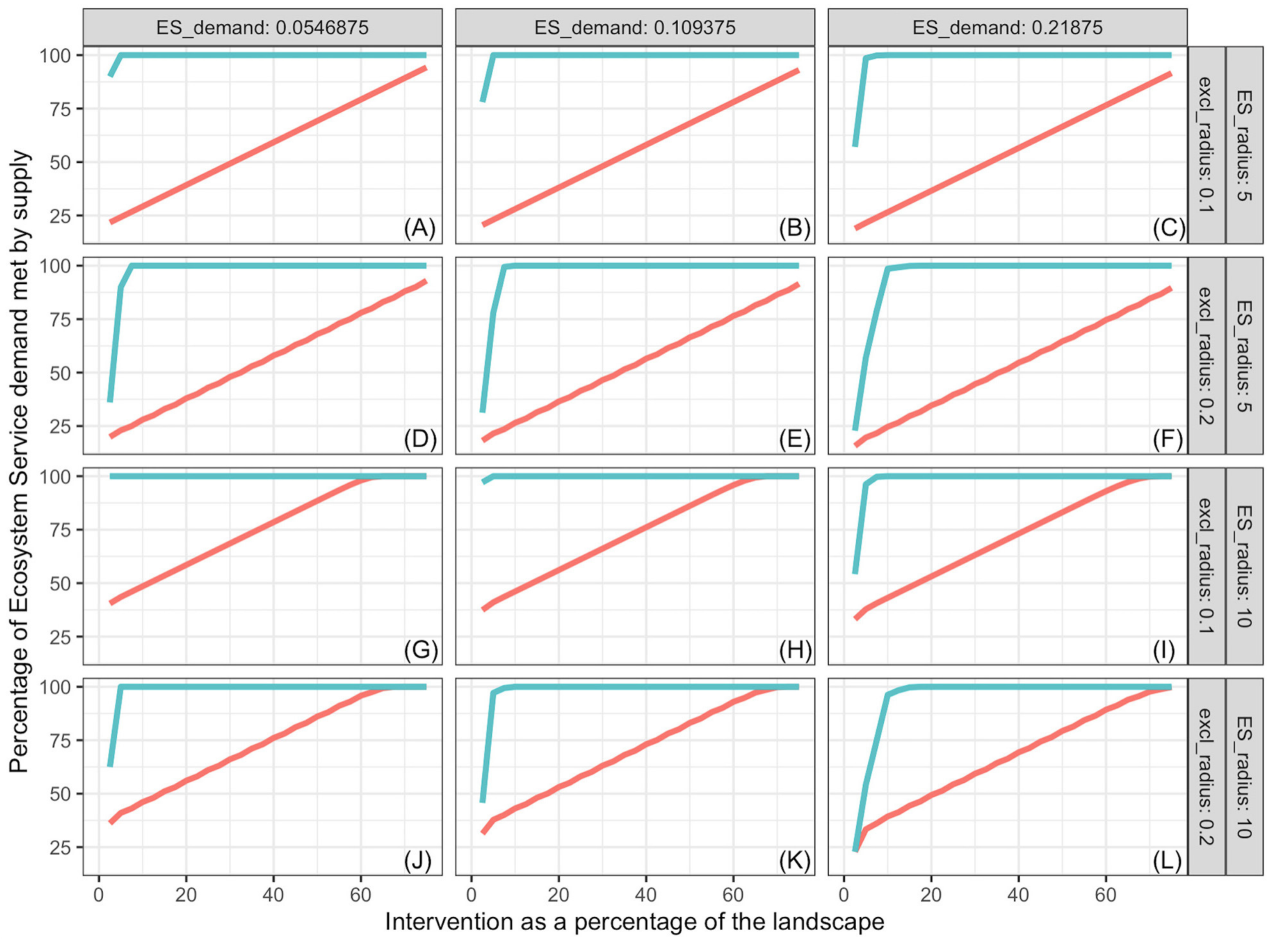

FIGURE 5 | Pollination services provided by bumblebees as a function of proportion of landscape that receives intervention, ES demand (columns), supply kernel radius and exclusion radius (rows), and distribution of interventions. The intervention is creation of nesting habitat and introduction of foundation colonies of bumblebees. Blue lines represent interventions spread out evenly over the landscape; red lines represent results when all the intervention is performed as a compact area in the center of the landscape. Some blue lines cover the red lines. Labels **(A–L)** refer to the combinations of ES demand, supply kernel radius and exclusion radius indicated on the columns and rows of the figure grid.

maintenance services, according to the Common International Classification of Ecosystem Services (CICES) V5.1 (Haines-Young and Potschin, 2018). Strictly, carbon sequestration is not an ecosystem service, but it can be used as a proxy for the regulating effect it can have on the atmosphere. I do not propose a relationship between the class of ES and the applicability of the model, because ES classifications [reviewed by Czúcz et al. (2018)] seem to be based more on type of function (provisioning, regulation, cultural) whereas the model I describe focuses on relationships between spatial scales of interventions and the ES affected by those interventions. I did not select the interventions and ES analyzed on the basis of the class of ES, but to represent contrasting scales of ecological fields. For example, the analysis would be different for the oak interventions if the focal ES were aesthetic value, which has a much larger kernel than that for soil organic matter. Thus, at least in principle, the approach is general and not restricted to specific types of ES. Any intervention and related ES can be subjected to the analysis proposed, but of course, the feasibility of interventions and the effectiveness of the ES will depend on the specific situation considered.

Kernel and Exclusion Radius

The ratio kernel:exclusion radius is a dimensionless metric of the effectiveness of functional units to provide ES beyond interventions. For the organisms and services considered here, it makes sense that the exclusion radius is smaller than the kernel radius. The area over which the service is supplied extends well-beyond the space occupied and preempted by each ES producing unit. However, in the case of plant and soil services, the exclusion and kernel radii can be very similar, because most processes that involve herbaceous plants and their soil involve movement over short distances. The FU kernel could be smaller than the space occupied by the unit, for example if the ES responds in a highly non-linear manner to the action of a FU, with a positive threshold.

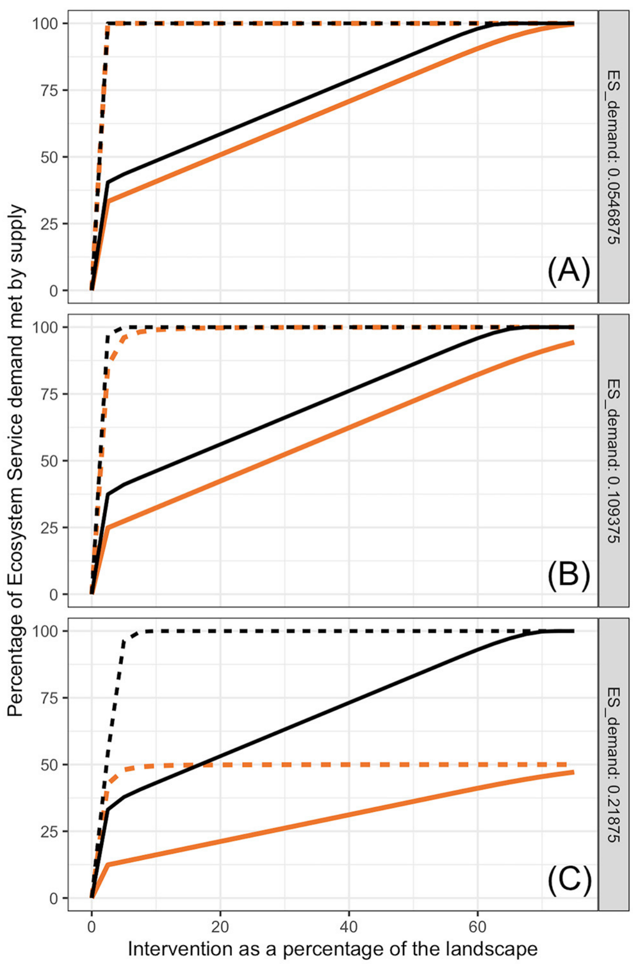

FIGURE 6 | Hypothetical effects of interactions between ES producing units on proportion of ES demand met. Black lines represent the same cases of bumblebees in (**Figures 4G–I**). Orange lines represent what would happen if supply of services equals the value provided by the nearest kernel (bee colony) only. Solid lines are for compact distribution of intervention and dashed lines are for evenly distributed patches, each with size equal to the minimum needed to establish a colony.

Ecosystem service kernels do not have to be constant for each ES producing unit but can adapt to the context. Wu et al. (1985) provide a modeling framework for temporally variable ecological fields of water and nutrients for plants. Mobile and adaptable predator like a Northern Harrier can adjust its hunting range and territory size depending on demand (prey density) and Northern Harrier population density (Norman and Jones, 1984; Jenner et al., 2011; Valeix et al., 2012; Kittle et al., 2015). Unlike what I simulated, Northern Harriers can expand their territory when prey density is low and contract it when it is high or when there are competitors nearby. It is possible that in all cases, the whole unit of ES service is provided within the modified kernel, and thus, the negative effects of increasing demand or competition on proportion of demand met would be mitigated. Species with adaptable kernels would be more efficient at meeting ES demand and less susceptible to the effects of spatial distribution of interventions than what is shown in the simulations I present. I expect that organisms that are mobile, fast relative to their range and lifespan, and with better mechanisms to gather and store information, are more likely to exhibit more dynamically adaptable kernels.

Spatial Distribution of Interventions

Results show that in general, spreading the intervention increases the effectiveness of ES supply relative to compact intervention areas. However, these results are completely dependent on the fact that the intervention was spread out into patches that were of radius equal to the exclusion or minimal radius of intervention necessary for one ES producing unit (nest, colony, plant). In fact, the spatial distribution of intervention areas can be managed to promote services of a specific kind and scale.

This conceptual framework to manage supply of ES can be extended by considering the spatial distribution of interventions across a large range of resolutions in relation to the "salient" or inherent scales at which FUs operate or integrate their environment. In general, larger and longer-lived organisms integrate resources over larger spaces and longer times, but there are notable exceptions. For example, individual bumblebees and even whole colonies are very small and short lived relative to the large areas over which they forage. Up to this point, interventions have been considered to be convex spatial extensions where all points inside an intervention patch receive the intervention. We can consider other feasible spatial distributions of interventions where resource density depends on the scale of analysis (Milne et al., 1992; Ritchie, 1998). For example, consider the seeding of native bunchgrasses as an intervention to create habitat for Northern Harriers. Areas can be drill seeded with various distances between rows, thus changing the grain of the intervention. From the Northern Harrier's point of view, which integrates information at a large scale, areas planted with rows that are 1 m apart are likely perceived as suitable nesting habitat. Conversely, the same grassland is perceived as alternating bands of suitable and unsuitable habitat by small organisms (say aphids and ladybugs) that live on the surface of the grass. Reducing the distance of rows to 0.5 m will not change the amount of Northern Harrier habitat, but it will potentially double the habitat area for aphids and ladybugs.

Further, consider the same amount of an intervention that can be used both for bumblebee and Northern Harrier nesting habitat. If the intervention is spread out into patches smaller than those needed for bumblebee habitat and far enough from each other that they are perceived as separate patches by both species, the intervention will generate neither pollination nor predation services. The same amount of intervention could be applied in separate patches of sufficient size as in the bumblebee simulations, thus generating abundant pollination but no predation services. Further increases in patch size or reductions in distance between patches would accomplish both services. Densely packed patches, each too small for bumblebees, could constitute Northern Harrier habitat, thus providing only predation services. By using designed spatial distributions of interventions with fractal-like properties, it may be possible to promote different compositions of ES supply by creating patchiness at multiple species and function-specific scales.

Ritchie and Olff (1999) showed that the fractal nature of habitat, food and resources frequently observed in nature can explain patterns of diversity. Species that use the same resources but that differ in size need to use different patches because of the relationship between their requirements and the resolutions at which they perceive and explore their habitat. Simply put, larger species require large patches with lower concentration of resources than smaller ones (Laca et al., 2010; Sensenig et al., 2010). Foragers have specific foraging scales, the size of the space searched for food at any instant in time (Ritchie, 1998), and the resolution with which they search for resources needs to balance the rates at which they acquire and spend resources. The idea can be extended to resources other than those contained in food, such as nesting locations. The present model applies the concepts presented by Ritchie and Olff (1999) in reverse: instead of using them to explain patterns of diversity as a function of natural spatial patterns of resources, I propose that spatial patterns of interventions can be used to promote specific patterns of community composition that provide the ES demanded.

Obviously, control of spatial distribution of interventions is not a new concept, but my claim is that its potential has barely been tapped. For example, intercropping has probably been used for millennia, and it has a prominent place for the sustainable intensification of agriculture. A recent global meta-analysis reveals that on average intercrops produce 38% more gross energy and 33% more gross incomes using 23% less land (Martin-Guay et al., 2018). Multiple ecological functions and interactions are likely to be involved in the greater efficiency of intercrops, such as niche complementarity, temporal niche differentiation (Yu et al., 2015), biodiversity of natural enemies, demographic limitation on pest populations, mutualism and microenvironmental modification. All of these have a spatial nature that can be thought of as kernels of influence with a variety of dynamic extents. Whereas, Martin-Guay et al. (2018) did not detect effects of spatial distribution of crop species ("intercropping pattern": rows, strips or mixed) on the land equivalent ratio (a measure of overall intercropping advantage), Yu et al. (2015) found a significant gradient where the land equivalent ratio of intercropping increased gradually from mixed to row to strips. In any case, and aside from the uncertainty implicit in failure to statistically detect differences, the lack of effects of intercropping pattern has to be taken within the context that there was a clear difference between sole crops and intercropping. The point is that "sole" crops differ from intercropping by the distance between the species. There must be a strip width (i.e., degree of interspersion or more generally, spatial pattern) at which intercropping becomes adjacent sole crops. Thus, the difference found between intercropping and monoculture cropping implies an effect of spatial distribution of the component crops. Industrialization of agriculture has taken us in the path of large uniform monoculture fields, with all the commensurate specializations in mechanization, distribution and marketing cultures that make change difficult. But imagine the potential to sustainably increase the production of multiple ecosystem services by creating agro-ecological landscapes where spatial distributions of seeding interventions are tailored to provide what is demanded. I surmise that research in this area has been constrained by the scales of technology, but as "precision" technology continues to develop, need and opportunities for research on spatial interactions and effects across a continuum of scales will increase.

In practice, the best amount and spatial distribution of interventions is determined by many factors beyond the spatial ecology of organisms and functions involved in the creation and delivery of ES. Opportunity and cost are probably two of the most important factors that weigh in to determine a good allocation of interventions. In some cases, costs will increase with the complexity of the spatial distribution of interventions. For example, setting up and maintaining multiple bumblebee nests in a single large patch is easier and cheaper than spreading them evenly over the extent of an orchard. As a matter of fact, domestic bee colonies are usually managed in large groups that result in less than optimal pollination over the whole orchard. Cunningham et al. (2016) clearly showed that in spite of the ability to fly and forage over long distances, pollination activity declines dramatically with distance to the colony, and that for a given overall density of colonies, a more uniform distribution of colonies leads to increased pollination and fruit set. For a given landscape-level density of colonies per ha, the optimal combination of number of colonies per placement and distance between placements is the one for which the cost of adding one placement equals the gains from the additional fruit set achieved.

Humans and institutions are crucial agents in the organization and function of landscapes. People and institutions create demand, set prices, generate and distribute information, create, manage and modify spatial distribution channels. Decisions by individuals, groups and institutions, just like ecological functions, have specific reaches and spatial distributions. One problem may be a disconnect between the reach of agent's decisions, or the reach of the information used for agent decisions, and the spatial characteristics of the functions affected. For example, Inogwabini (2020) wrote:

"It is here, in describing spatial functions that conservation has its entire place; not only because within the landscapes there are protected areas but also because each functional space should have a mode of usage that will integrate the principle of durability. Land use becomes, therefore, a means through which to integrate conservation and sustainable livelihood. However, one needs to acknowledge that we are in a human-dominated landscape. That means conservation stakeholders had to evaluate not only the viability of proposed zoning and their effects on biodiversity across this large spatial scale, but also to project ecological, social, and economic influences that would alter the equilibrium of interactions between human and biological diversity across the landscape in a long-term perspective."

The topic of spatial distribution of interventions is related to and might inform the land sharing vs. land sparing framework. I offer these comments with caution, because the sharing vs. sparing debate is vastly more general and complex than the specific model for quantification of matched ES demand I present in this work. Moreover, the sharing-sparing debate is primarily focused on food production, whereas I focus on the supply of ES demanded. Phalan (2018) wrote:

"The land sparing-sharing framework originated as a model for quantifying and understanding the implications for wild species of using land in different ways to produce food. It is based on the idea that there are two main ways to reduce the impacts of farming on wild species—making farmland itself more wildlife-friendly, or making more space for unfarmed habitats—and on the observation that there is a tension between these two sorts of interventions."

The present model and approach do not inherently imply any support for either extreme of the "sparing-sharing" debate, but they align almost completely with the concept of "multiple-scale land sparing" where food production and conservation of wild species is approached through a strategy of nested hierarchical scales of actions and ecological functions (Ekroos et al., 2016). Based on the concepts of spatial and temporal scales presented in this work, at least part of the difference between sparing and sharing is a difference in scale. Simply put, sparing could be seen as sharing with a very large grain, where the intervention is the protection of areas of natural habitat. Under the reasonable assumption that most if not all species are related to the production of some ES, sparing can also be seen as interventions applied to promote the services provided by species that require large exclusion radius and have a kernel:exclusion radius ratio close to 1.

CONCLUSION

Although I only explored the effects of spatial distributions of interventions, the concepts are easily extended to the space-time continuum (e.g., Wu et al., 1985). Interventions with various durations might be distributed independently over space and time. The specific effects of each distribution on ecosystem services and multiple functions in interspersed agricultural, wild and urban landscapes can be surprisingly non-linear and counterintuitive, even when just a few simple mechanisms are involved, as I show in this work. Simultaneous manipulation of many of the dimensions of spatio-temporal distributions of interventions at the appropriate scales opens a myriad of management options in the search for sustainable landscapes.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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Integrating Digital Technologies to Aid Grassland Productivity and Sustainability

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Digital technologies provide an opportunity to further increase the sustainability and productivity of grasslands and rangelands. Three resources are key to that change. These are the soil on which forage grows, the forages that grow on those soils and the animals that use the forage resource as food. This paper describes elements of technologies to measure and monitor these resources and provides some insights on combining that knowledge and controlling the animal's utilization through virtual fencing. There are many potential challenges to the application of digital technologies to pastoral farming. These often require the calibration of digital signals to define biophysical characteristics. The significant repository of historic data of pasture growth over many geo-climatic regions, for example, provides New Zealand with an opportunity to accelerate that development. Future advances in rangeland use, nutrient deposition, greenhouse gas emissions and the provision and utilization of high quality and quantity will be enabled by the application of digital technologies at scale, under the control of virtual fencing. Digital technologies may provide the means to maintain or enhance ruminant production from grassland in a sustainable operating space into the future.

Keywords: uncertainty, spectral analysis, grazing control, digital, animal phenotyping

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INTRODUCTION

Digital technologies have the potential to change the way rangeland and grassland are managed. The rise of the internet-of-things and cloud storage has changed how we collect, store, and process data. Previous systems were paper-based and often transient. Users tended to internalize the knowledge gained from data collection without further storage or application. Such systems have been traditional in many cultures, where learning is passed down through generations, often using spoken histories. Written knowledge has developed significantly with formal learning approaches and records, but individual learnings at a farm or business scale have often still been assigned to experiential, with knowledge passed verbally among participants.

Digital technologies now enable both the collection and storage of data in perpetuity. This data can be transferred easily among users and interpreted remotely. Huge amounts of data, representing numbers, words, sounds and images, can be stored this way because it takes up very little physical space. This also means that the data can be transmitted to, and interpreted by, other users, including machines. The universal nature of digital data provides an enormous opportunity to collect, store, share and interpret data. New information and knowledge can be created through that interpretation.

The activities of humans across the globe has pushed natural systems to, and potentially beyond, their limits (Steffen et al., 2015). While agricultural intensification may be at the forefront of concerns (Campbell et al., 2017), ruminant grazing systems may provide an opportunity to utilize the unique resource that grassland and rangeland provides. This would enable the continued delivery of valuable products without the primary use of crops for animal production (McCoard et al., 2020).

However, current trends in production-driven grassland systems are toward intensification and highly productive and specialized breeds. For example, the Angus beef cattle breed makes up ∼60% of the *Bos taurus* cattle numbers in the world. The trend toward using these highly productive cattle also poses a threat to sustainable land use. Spiegal et al. (2019) used GPS tracking to demonstrate that highly productive cattle (Angus x Hereford) generated twice as many hotspots (mass urine and fecal deposition sites) and less use of native food supplies than the traditional Raramuri Criollo cattle in New Mexico rangeland.

These trends toward intensification and specialization have led to pastoral degradation, reductions in biodiversity, fire protection and ecosystems services such as water provision (Battaglini et al., 2014). Shifts from traditional breeds and approaches also threaten co-developed systems such as the sylvo-pastoral dehesas system in Spain and the montados in Portugal that deliver high ecological and biodiversity values alongside animal products (Buckwell and Nadeu, 2018).

Digital technologies may be able to optimize animal productivity while minimizing environmental impacts. Technologies that provide a unique advantage for grassland and rangeland are those that can be used to characterize of the soil, the pasture/forage resources and the grazing animals. The characterization of each of these provides information on potential intervention and management options. Control of the grazing animal has traditionally been through herding and fencing to place animals in the right part of the environment to meet their nutritional needs, while providing the potential to rest some parts of the grassland to provide feed in the future. The development of virtual fencing technologies has added an extra dimension to both spatial and temporal control of animal grazing and nutrient transfer events. These technologies are not without their limitations. Algorithms need to be created, calibrated and validated to predict biophysical information from digital data. Data, both digital and biophysical contains uncertainty through both the accuracy and precision of measurement (Czarnecki and Podolak, 2013) and inherent expression of the observation (Steel and Torrie, 1980).

New Zealand has a significant history of characterizing this pasture production to understand that variation and provide resources to assist farmers in enterprise choice and systems design. These variations in climatic conditions result in large variation in the amount and seasonal distribution of pasture production (e.g., Radcliffe, 1974; Baars, 1976; Piggot et al., 1978; Roberts and Thomson, 1984). Enterprises are chosen to suit local pasture growth conditions, aimed at maximizing pasture use and minimizing imported feed (McCall and Sheath, 1993). The grazing systems employed are supplemented by some forage cropping to provide extra feed, most often to augment winter and/or summer feed supply depending on the regional imbalance (Stevens, 2009). The most regularly used forage crops, brassicas and beets, provide feed in winter at higher altitudes or higher latitudes. In these instances, usually no more than 5% of the farm might be planted in forage crops.

The range of New Zealand landscapes and their variability, both spatially and temporally, provides the opportunity for unique insight into the role and performance of digital technologies and their potential application on grazed landscapes. Documented characterization of soils, pastures and animals provides a base from which to build, and to use for calibration and reference when developing new digital technologies.

This paper explores a set of critical technologies with which the authors are currently working. It provides a perspective on the implementation of those technologies. This paper aims to provide stimulation of thinking for the reader to facilitate the integration of digital technologies to provide sustainable, productive future landscapes, using New Zealand grassland examples.

CHARACTERIZING THE LANDSCAPE RESOURCES

The ability to quantify the current resource and predict future pasture supply becomes of immense value for resource management and productive outcomes. Quantification of current and future states also provides opportunity to minimize the impacts of management on environmental outcomes such as soil disturbance, water quality and greenhouse gas emissions.

While conventional science has provided a significant base for measuring and understanding the soil and plant resources of grazing ecosystems, often these resources are expensive to implement and have been defined at relatively large scales such as farm, catchment, region or per km^2. Refining both the temporal and spatial variations in those resources will drive innovation in the efficient use of, and change in the use of, those resources.

Many grasslands and rangelands are in remote locations, have significant scale per enterprise and have topography that is unsuited for conventional direct measurement techniques. Therefore, direct measurement of soil and pasture is time consuming and expensive especially if high resolution variation is present. The most promising options for broad scale grassland farming is spectral analysis for both plants (Edirisinghe et al., 2012) and soils (Yule et al., 2015).

Using remote sensing via spectral analysis can collect large amounts of data quickly and relatively inexpensively at a scale that can be varied from patch to paddock to farm. Imagery can capture the spectra of radiation that is reflected from the earth's surface (Rouse et al., 1974). These spectra consist of the range of radiation that is received by the earth's surface from the sun, e.g., ultra-violet, visual and infra-red. Spectral analysis uses the principle that the spectra of radiation that is reflected from plants and soils can be calibrated to determine the type of vegetation, the area of exposed soil, the density of plant life and the chemical composition of the plants (Rouse et al., 1974). This information can be collected in a variety of ways, with rapid collection in remote conditions being enabled through satellite imagery or aircraft surveys (Yule et al., 2015).

Resolution has increased, both from satellite, from 1.15 to 3 m^2/pixel, and higher with drone footage. This means that the imagery can be used for general biomass estimation (Rouse et al., 1974), down to prediction at the grazing animal scale (Dymond et al., 2006; Edirisinghe et al., 2012). This then enables an increased range of potential decision-making layers or intervention points for management, across large tracts of grassland or rangeland.

CHARACTERIZING GRAZING ANIMALS

Where animals go and what they do in their environment has significant implications for resource use efficiency and environmental impacts, both positive and negative. The technological advances in micro-processors, genetic/genomic technologies and big data management has created the opportunity to scan large numbers of animals using advanced technologies to gather in-depth data on behavior and personalities. The combination of data from these technologies can then be used to make more informed animal selection decisions, matching animal personalities to environments to improve rangeland utilization and environmental impact. Developing grazing and environmental personalities of animals using global positioning system (GPS), inertial measurement (activity sensors) and urine sensors is explored here as a means of characterizing the grazing ruminant.

Studies of rangeland utilization of farmed ruminants using GPS units has been able to identify different individual behaviors. Bailey et al. (2004) demonstrated that individuals within a herd consistently utilized different terrain and resources than other individuals. Wesley et al. (2012) also demonstrated that individuals that consumed supplements faster in confinement utilized larger rangeland areas and spent less time close to water than individuals that consumed supplement slower. Bailey et al. (2015) was able to associate utilization of terrain type to genotype. This work indicated that several quantitative trait locus (QTL) accounted for significant proportions of variation in terrain use indexes.

The ability to add other sensors to GPS collars has also allowed more behaviors to be captured. GPS units now commonly have multiple axis accelerometers as activity sensors and, when combined with spatial data, can define behaviors such as grazing, traveling and resting (Bailey et al., 2018).

This opportunity to collect both spatial and temporal data of whole herds will allow new insight into grazing behavior, animal impacts and identification of animal genotype suitable for different environments (Bailey et al., 2015). This may increase productive potential and biodiversity retention while minimizing environmental harm and fire risk.

Animal urination is a particularly sensitive activity as it concentrates nitrogen in the environment. This has an important part to play in redistribution of nutrients and creation of hotspots of potential water contamination (Castillo et al., 2000).

Urine sensor technology has gained increasing attention to measure urine excretion from grazing livestock for developing strategies to mitigate farm nitrogen loss. This technology ranges in complexity from measuring the time of each urination event and volume using flow meters or thermistors (e.g., Betteridge et al., 2010; Ravera et al., 2015) to also measure urine nitrogen concentration (Betteridge et al., 2010; Shepherd et al., 2017a).

Urine sensor technology has been used to assess the effect of different forages on urine excretion from livestock (Bryant et al., 2017), and compare changes in farm systems on livestock urine nitrogen production (Shepherd et al., 2017b). Moreover, detailed information on the diurnal and spatial (linked with GPS technology) patterns in urination characteristics could be harnessed to develop new nitrogen mitigation strategies.

DIRECTING ANIMALS IN THE ENVIRONMENT

Benefits of understanding the pasture and soil resources, and the grazing behaviors and preferences of the livestock can often only be captured by directing livestock to the right part of the landscape. Without control of grazing livestock, landscapes are often under- or over-utilized.

Understocking may result in significant shifts in biodiversity and ecosystem type. For example, the ingress of woody weeds has been identified as a significant issue in many environments (e.g., Archer et al., 2001). Estimates of safe operating limits in Europe identify the need for ruminants in uncultivable grasslands to maintain biodiversity and reduce fire risk (Buckwell and Nadeu, 2018).

Overstocking is also a significant concern, often in regions where control of animals in grasslands and rangelands cannot be implemented. A lack of property rights and low social capital often leads to a lack of resource management due to the "tragedy of the commons." Often these grazing systems are only "overstocked" because severe continuous grazing restricts pasture growth (Hodgson, 1990). The impacts of ruminants on the landscape are also associated with the uneven distribution of grazing (Bailey, 2005). Controlling animals in the environment provides a solution to overgrazing, uneven grazing and nutrient redistribution.

Controlling animals in a domesticated setting has a documented history of 8,000 to 10,000 years. The opportunity to protect animals, control feed utilization and improve environmental outcomes has made fences indispensable in modern livestock farming. However, current fencing methods are costly, time consuming and potentially not available to all, restricting their implementation and potential benefits. Virtual fencing has enabled new opportunities for animal containment through recent advances in training techniques, coupled with rapid changes in digital technology. Virtual fencing (or herding), is explored in its ability to completely rethink both capital and resource use paradigms, as well as controlling environmental impacts of the grazing animal.

There are several virtual herding systems in development, all based on each animal wearing technology housed in a neckband or collar. These include eShepherd®, NoFence®, Halter®, and Vence®. These are all based on avoidance learning using the cognitive activation theory of stress (Ursin and Eriksen, 2004). This describes a scenario where animals learn to respond to a non-aversive audio stimulus to avoid an aversive electrical pulse. Successful learning occurs when the animal perceives cues to be predictable (audio warning always precedes a pulse) and controllable (operant response to the audio cue prevents receiving the pulse) and an acceptable welfare outcome ensues. After the initial learning period (~6 approaches for 50% of cattle to learn; Campbell et al., 2018), and with coupling of the application of the audio warning consistently at every approach event, responses indicate that cattle learn the situation has high predictability and can avoid the electrical stimulation by responding to the audio cue alone (Lee et al., 2008, 2009).

A GPS receiver in a collar is used to define the area available for the animal to access. The information to set the accessible area is loaded via remote systems such as LoRa or cellular networks, once defined by the user in the associated software. Other sensors in the collar help determine the response of the fence algorithm. The e-Shepherd® for example uses the accelerometer within the collar to detect an animal running toward a virtual fence. The herding software is disabled, recognizing that a charging animal cannot be successfully contained by the training and control of the electric stimulus. The program within the collar tracks the animal and when the animal has stopped running, the fence is reset in such a way to herd the animal back to the original accessible area.

COMBINING TECHNOLOGIES TO OPTIMIZE GRASSLAND MANAGEMENT

Knowing where animals are going, how far they travel and what they do when they get there introduces many opportunities. How far an animal travels directly influences their energy requirements. For example, ewe lambs in a semi-intensive grazing environment traveled an average of 3.4 km/day (Johnson, unpublished data) while ewes grazing a large extensive environment traveled 5.3 km/day (Steer, 2012). However, there is large variability between individuals with 3–5-fold differences reported in the above studies, which is both repeatable and heritable (Johnson, unpublished data). Associated with this range of movements is the proportion of the potential grazing area an individual animal encounters. This provides some individuals with much greater access to the feed resource, providing potential benefits in the type and quality of feed available.

Comparative movement and extension of home range also influences the deposition of feces and urine, so altering the pattern and intensity of hot spots in the environment (Spiegal et al., 2019). The use of urine sensors to characterize the relative variation in urine deposition of animals could also be used to allocate appropriate animals to different environments, depending on the sensitivity of that environment to nitrogen overloading.

Using activity sensors to understand individual animal intakes would improve animal management through matching feed requirements with feed availability. It would also allow detection of reduced intakes. Indoor feed intake studies in sheep (and cattle) have demonstrated large between-animal variability in how animals manage their daily intake. This includes number of daily feeding events, the duration of these feeding events and the rate of intake during feeding events. If intake data could be integrated with the GPS data, it would unlock even more information about variability in grazing to be matched with pasture disappearance and soil mineral maps.

When combined to the mob level, pasture use across the landscape can be mapped. This can be combined with satellite NDVI estimates of pasture cover and soil mineral maps to understand the interactions between the soil, pasture and animal (Trotter et al., 2018). This information could be used in management decisions such as changes to grazing plans, retirement from grazing for alternative uses, differential fertilizer application, and reductions in nitrogen leaching potential.

While collars on animals provide a starting point for generating new knowledge about the animal and its use of its environment, the technology also provides an enabling opportunity through directing livestock into specific parts of the environment, or exclusion from other parts. The use of both a GPS and virtual fence, and many sensors and interpretive algorithms in a permanent collar worn by the grazing ruminant provides a range of potential benefits (**Table 1**).

Many farms face challenges with the installation and maintenance of fencing infrastructure (Stevens et al., 2019a). This may be due to the age of current fencing, to the erosion-prone nature of some soil types, to flooding or snow damage. The availability of virtual fencing can provide options to tailor new fencing configurations that optimize the use of the landscape. It is envisaged that early adopters farming beef in hill country will take up the virtual fencing for waterway protection in New Zealand due to government implementation of new regulations restricting waterway access for livestock. New Zealand hill country has many waterways which require livestock exclusion. The difficult terrain makes physical fencing extremely costly (Obadovic et al., 2020) and presents logistical challenges.

The much finer control of livestock grazing provides an opportunity to increase resource use efficiency, while reducing secondary losses from the system, such as nitrate through leaching and soil through sediment movement. Controlling where the animals graze and congregate can alter the distribution of nutrients in the environment. Varying this position over a series of grazing events will enable the redistribution of nutrients around the landscape, reducing the need for fertilizer inputs.

An example of innovative application of this technology is livestock security. In some parts of the world, being able to prove both ownership and location of livestock may enable greater capital investment in livestock farming, by having greater surety of current values of livestock.

TABLE 1 | A range of issues and solutions that digital sensors may provide when linked to the collar containing virtual herding technology, identified at a lead-user workshop in 2019, Hamilton, New Zealand.

Issue	Solution
Security	GPS location links to on-farm biosecurity systems Surety of livestock placement reduces farmer stress Ownership and security of livestock secure finance
Health and Welfare	Animal health/welfare links with software Proof of welfare/health is provided
Animal breeding	Algorithms and additional tech such as proximity sensors enable prediction of mating and birthing events, dam/calf interactions etc. Grazing behaviors are developed for breeding
Feed management	Lower need for winter crops as better pasture utilization Links to forage measurement technologies mean that animal nutrition is optimized for any situation An understanding of range use enables development of tailored grazing plans for parts of the herd Control of intake on crops can be achieved
Labor	Herding options allow for reduction in labor requirements
Environmental	Algorithms predict GHG outputs based on grazing and rumination behavior Compliance around winter grazing is near perfect Sensors are active in confirming animal placement GIS information is linked to the collar to automatically control animal movement, depending on need

LIMITATIONS AND CHALLENGES

While digital technologies show promise they all have several limitations. Calibration and validation are key to the success of digital technologies. This is because each data measure is generally only an approximation of a true value or distribution—even though there may be hundreds, thousands or millions of them. Each data point has varying levels of quality and uncertainty, for example, data collected by physical techniques vs. satellite sensing technologies. Quality and uncertainty are defined by the precision and accuracy of the data collected and expressed as the error that can be calculated from repeated sampling of any population (Steel and Torrie, 1980). Uncertainty in data, and therefore in all types of data science models, introduces the risk of poor decision outcomes because of biases, drift and lack of precision in individual sensor systems (Wolfert et al., 2017). Further, as the volume and variety of data increases, so do the uncertainties inherent within (Czarnecki and Podolak, 2013; Hariri et al., 2019)—big data is often subject to noise, incompleteness, bias and inconsistency (Hariri et al., 2019; Sharifi et al., 2020), and may often be disparate, dynamic, untrustworthy, and inter-related (Wang and Jones, 2017).

Using spectral data for soil and plant characterization has several known limitations. These include spectral saturation, cloud cover, changing satellite angle and spatial resolution. For example, the Normalized Difference Vegetation Index (NDVI) uses the difference between near infrared, which is reflected by vegetation, and red light, which is absorbed by vegetation (gisgeography.com, 2017). As NDVI approaches the upper limit of 1.0 for pastures (around 3,500 kg DM/ha), the spectra become saturated lowering the accuracy of prediction. Another known issue is the inability to perform NDVI measurements where clouds cover the area of interest. That decreases the temporal resolution of data and requires producing weekly or monthly image composites to create cloud-free imagery. Spatial resolution has significant influence on the accuracy of the measurements. While the 250 m/px imagery available daily from MODIS Terra and Aqua satellites is potentially useful tool on a national scale, it tends to mask differences between different pasture cover types and provide higher NDVI values than higher resolution satellite imagery for the same area, which eventually lead to overestimation of dry matter.

These issues mean that developing algorithms which are calibrated and validated for farms located across a range of environments remains very challenging. The work of Dymond et al. (2006) and the Pastures from Space project in Australia (Hill et al., 2004) have demonstrated potential, yet the scale of ground-truthing required remains a major obstacle. Future machine-learning and artificial intelligence building off smaller data sets holds significant promise. Lack of reliable field biomass measurements for farms located in different regions and topography is another problem that decreases the transferability of calibrations. Issues such as shading due to satellite and sun angle in hill country and the amount of dead matter in pasture may compromise the ability of a single calibration to provide repeatable prediction of herbage mass (Edirisinghe et al., 2012).

Technical challenges are apparent in creating algorithms that can be universally applied. Digital approaches are nearing a point where the precision of imagery and machine learning may help solve the calibration/validation issue. This would rely on the ability to utilize herbage mass data that was manually collected on-farm. Industry and government investment to collect and utilize farm data are increasing (e.g., FarmIQ, Farmax; Isaacs and White, 2016).

The on-going requirement for an evolving calibration of spectral analysis data poses a significant problem in situations where biomass estimates are not made. In the New Zealand context dairy farm managers often assess and report pasture biomass, albeit using a trained eye assessment (Eastwood and Dela Rue, 2017). In this circumstance machine learning or algorithm development could provide an on-going adjustment of image analysis to modify imagery interpretation, allowing the technology to be continually applied. When ground-truthing data is not available, this cannot happen. Therefore, farming systems that already measure features such as pasture quantity and quality will be much better placed to develop techniques to capture the value of these digital technologies.

One ground-based technology has been developed to address some of these issues. Farmote Systems® uses an infra-red-light source positioned within each paddock operating at night. It automatically returns data via a radio network and delivers a decision-ready report to graziers. It also uses a cross-reference to satellite imagery as available (Milsom et al., 2019). This type of approach mitigates several of the concerns of spectral analysis. For example, taking a reading at night, at near ground-level removes interference from other radiation sources. Cross-referencing provides the opportunity to modify calibrations to improve accuracy. Automated recording and reporting remove significant labor requirements to gather data. This type of technology integration provides a good example of capturing the value of digital approaches.

Technologies that reside on animals have unique issues that may limit use. Animal welfare concerns are potentially significant as harnesses and fitting may hinder movement, disrupt behavior and injure the animal. These issues are being addressed through thoughtful design and constant improvement. The general public have raised concerns about technologies such as virtual fencing. Many of the studies of virtual fencing have been directed to address these concerns (e.g., Campbell et al., 2019), though efforts to provide that information to the general public will also need to be made to aid with its use (Stampa et al., 2020).

Advances in battery engineering, computing hardware, and satellite networks have improved since the initial release in 1991 bringing animal tracking into the realm of big data research (Kays et al., 2015). However, many commercially available units still retail for considerable costs and have ongoing software licensing and data management fees. The rise of open source hardware has allowed the production of self-managed low-cost GPS units to be developed (Cain and Cross, 2018) allowing access to this technology to the masses.

Calibration requires significant resources and is often specific to one configuration of the technology. Data from animal-based sensors available through publication has been restricted to small scale studies, often with farm management objectives in mind, or the development of prediction equations for specific traits. Often calibrations are proprietary to the technology developer.

Handling and interpreting huge amounts of available data is key to extracting value in complex decision-making. Many decisions may only require simple data to make yes/no decisions. For example, knowing a critical temperature boundary has been exceeded may provide a decision-making point to declare food unsafe. Complex decisions, such as those required to manage grazing systems, use much more data, and integrate data from many sources (Gray et al., 2005).

Sources of available data will include climate, soil, plant, animal, product, and consumer (**Table 2**). Insights will be enhanced by understanding the associations or relationships between these variables. This data needs to be collated and integrated with technologies such as machine and deep learning, augmented reality and multi-functional decision-making. This will provide an understanding of current state of the world and generate opportunities to predict or visualize what might happen and to (re)direct for the best outcome(s).

TABLE 2 | An example of the sources and types of data that will be available to collate and integrate to inform current state, predict future states, and direct decision-making.

Data source	Data type
Climate	Temperature, solar radiation, precipitation, wind, humidity
Soil	Water holding capacity, nutrient status, physical structure, leaching, runoff, biota
Pasture/plant	Species, growth rate, crop yields, defoliation tolerance, nutrient content, grazed area
Animal	Species, milk, meat, fiber, health status, reproductive status, nutritional requirements, liveweight, body condition, well-being
Product	Type, volume, waste, price, processed form, safety, quality, source
Consumer	Preferences, beliefs, purchasing behavior, expectations

APPROXIMATION AND UNCERTAINTY

Biological systems are inherently variable. For example, pasture growth in a single paddock will vary greatly depending on factors such as microclimate, soil fertility and previous urine and fecal deposition. This is then overlaid by the dietary preferences of the grazing animal and their avoidance of undesirable parts of the pasture. Thus, even at the finest level, the scale at which we can collect data guarantees that the biological system introduces another layer of uncertainty, over and above that of the measurement techniques, before an outcome is realized.

The risk of poor decision outcomes is particularly true in analytics that combine non-traditional information sources such as rapidly arriving data from sensors, process models, qualitative information and user behavior (Wynne, 1992). Using multiple disparate data sources means compounding data uncertainty originating from the data collection, data curation and combination from multiple sources (Czarnecki and Podolak, 2013; Hariri et al., 2019).Communicating uncertainty in data can introduce further complexities, and uncertainties are sometimes ignored, or even explicitly denied (van der Bles et al., 2019). Uncertainty in the data collection, analysis and knowledge extension processes can lead to a lack of confidence in the resulting model outputs and decision made thereof. Communication of the uncertainties associated with findings from data modeling is vital, since, unless uncertainty is communicated effectively, decision-makers may put too much or too little faith in it (Fischhoff and Davis, 2014; van der Bles et al., 2019) leading to poor or unexpected outcomes (Meenken et al., 2020).

Matching the potential predictions and decisions of digital technologies with the expectations and experiences of the end-user will remain a challenge. This has effect in two ways. The first is the ability of the digital technologies and the data analysis to represent the biophysical situation accurately. For example, tools to measure pasture biomass need be calibrated to appropriate pastures (Eastwood and Dela Rue, 2017). If calibrations of the data, or its use in defining future states such as pasture growth, cannot match reality then the end user will dismiss the technology. Many technologies have suffered this in the past. The second effect is when the outcomes from digital data analysis provide new insights into the impacts of decision-making, or potential new ways of proceeding. In this instance the technology may be right, but not representative of the experience of the end user. In this situation, valuable progress may be dismissed.

Successful complex disparate data analysis will provide a) uncertainty evaluations that account for the combination of all types of data by applying the principles of metrological traceability and b) support decision making with excellent tools to communicate uncertainty. Quantitative and qualitative metrics of uncertainty both improve confidence in the validity of the information and provide evidence for the underlying quality of the model and data (Mastrandrea et al., 2010).

DISCUSSION

First steps in capturing the power of digital technologies will be small, as the technologies are not yet fully formed. Gains will be made in improving the fit of resources to productive potential of both the land and the animals. For example, grazing control may improve the utilization of the grassland resource, increasing both quality and quality of forage available. This would result in an initial increase in production via pasture utilization, and a secondary increase in stocking rates and/or an increase in animal performance. Interestingly, these outcomes may augment or deplete the environment depending on the pathway chosen by the grazier. If a grazier chooses stocking rate to capture the benefits, then more nutrient leakage (from urine and fecal deposition and treading damage) may result.

Scenario testing using fine-scale GIS data of topography and aspect, combined annual and perennial thistle density data and soil nutrient and water-holding data has been used to predict the relative economic benefits of thistle control on a complex hill property (Stevens et al., 2019b). This provides an example of how digital technologies can be used at fine scale to offer new insights into farm management options. This work utilized 64 potential pasture/thistle interactions in the range of micro-geoclimatic zones present on a single farm. While this may technically provide on-farm opportunities for increasing efficiency/profitability, the current fencing would not allow optimal pasture utilization. Adding virtual fencing would aid in capturing benefits that can now be predicted using digital technologies.

As the technologies are further refined then land managers may capture benefits by fitting practices to landscape and avoiding potential conflicts of changing productivity. Ecosystems services such as biodiversity, nutrient loss minimization and water harvesting may be improved through selective use of various landscapes. This selective use may involve both time and space, to for example, vary grazing near waterways, or restrict grazing access to specific times of the year when damage is minimized, and benefits enhanced. For example, using ruminants to graze pastures in spring to prevent fuel build-up in fire-prone areas, enabled by the use of virtual fencing.

Potentially the addition of new enterprises, or changes from current to future enterprises may occur. Benefits from increased utilization and productivity of pastures may allow land of higher quality to be released for other enterprises such as arable or horticultural use. The emergence of such enterprises will require a redistribution of labor and resources. It potentially may also result in shifts of power, depending on the relative profitability of each enterprise, influencing other outcomes such as social and environmental impacts.

For example, when adding legumes into a hill farm, Dodd et al. (2020) determined that significant increases in both pasture and animal production were achievable, while reducing nitrogen fertilizer inputs. Legume introduction was targeted at specific micro-geoclimatic zones on the farm, using GIS mapping. However, realizing those gains in practice will again require much more precision in livestock control and grazing, hence requiring these technologies to be enabled by virtual fencing.

However, using the data is not all that is required. Key to the success of applying any digital information is the ability to uniquely identify the data and assign it to a space and time. Therefore, the shift to digitization must be accompanied by not only data collection, but storage and categorization in a standardized way. Many farmers collect animal liveweights for example, but current collection and storage processes are fraught with problems which include data being confined to files which have no common or systematic naming protocols, have few unique identifiers and poor time stamp control. This then means that the data is difficult to decipher and utilize beyond the farm boundary.

Digital technologies come at a cost, both financially and in time. This can be a significant barrier to technology uptake. Thus, technologies will be adopted at different rates depending on the urgency and relative cost compared to other solutions. For example, Yang et al. (2021) found that the uptake of digital technologies varied both from region to region and between farms of different demographics and herd size, depending on economies of scale, access to capital, and current infrastructure constraints. In another example, the uptake of virtual herding technology may be driven by legislative change to waterway fencing regulation (Obadovic et al., 2020) with the cost of the technology be lower than the cost of conventional fencing.

CONCLUSIONS

Key to applying digital technologies to enhance the outcomes from grasslands and rangelands is understanding the roles and interactions between principle factors that influence the balance between productivity and sustainability. Using remote digital approaches to characterize the resource base with both spatial and temporal precision will unlock a range of new options to manage biophysical resources.

Characterizing animals will provide new opportunities to match grazing behaviors to plant and soil resources, improving sustainability. While, for example, variations in grazing style (animals with different bite size for example), may not have a direct effect on productivity, the rate of prehension and subsequent rumination may have a significant effect on the extent of digestion and potential greenhouse gas emissions.

Previous research on grazing behavior tested theories through varying pasture conditions, but key to applying digital technologies is to know what variation is available between animals. It will be the application of variability in the animal to harness the variability in the soil and pasture resource that will provide the step-change in resource use efficiency in grassland-based ruminant production systems. Understanding, interpreting, and discovering new insights into the data will underpin our ability to capture value as data adequately reflects practice.

Step-change will only be realized if livestock can be directed to appropriate niches within the landscape. Virtual herding technology provides that option. Finally, new business models that make use of the shared data will change our approaches to managing grasslands and its future production. The balance between efficiency, intensity and environmental impacts will be better understood and managed.

Integration of digital technologies may provide the means to maintain ruminant production from grasslands in a sustainable operating space. We must discern the difference between the fascinating and the important in the quest to develop digital solutions. However, we must also be able to recognize when the fascinating becomes the important.

AUTHOR CONTRIBUTIONS

DS coordinated the papers and wrote the Introduction, Characterizing the Landscape Resource, Directing Animals in the Environment, and Combining Technologies to Optimize Grassland Management. BT, PJ, and BW wrote Characterizing Grazing Animals. EM and JB wrote Approximation and Uncertainty. All authors contributed to Limitations and Challenges, Discussion, and Conclusions, provided editorial comment on the whole document, and approved the final version.

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REVIEW
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Opportunities to Apply Precision Livestock Management on Rangelands

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Precision livestock management has become a new field of study as the result of recent advancements in real-time global positioning system (GPS) tracking, accelerometer and other sensor technologies. Real-time tracking and accelerometer monitoring has the potential to remotely detect livestock disease, animal well-being and grazing distribution issues and notify ranchers and graziers so that they can respond as soon as possible. On-going research has shown that accelerometers can remotely monitor livestock behavior and detect activity changes that are associated with disease and parturition. GPS tracking can also detect parturition by monitoring the distance between a ewe and the remainder of the flock. Tracking also has the potential to detect water system failures. Combinations of GPS tracking and accelerometer monitoring may be more accurate than either device used by itself. Real-time GPS tracking can identify when livestock congregate in environmental sensitive areas which may allow managers the chance to respond before resource degradation occurs. Identification of genetic markers associated with terrain use, decreased cost of GPS tracking and novel tracking data processing should facilitate development of tools needed for genetic selection for cattle grazing distribution. Precision livestock management has potential to improve welfare of livestock grazing rangelands and forested lands, reduce labor costs and improve ranch profitability and improve the condition and sustainability of riparian areas and other environmental sensitive areas on grazing lands around the world.

Keywords: GPS tracking, well- being, grazing distribution, disease, accelerometer

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INTRODUCTION

Livestock operations that rely on rangelands and forested lands differ from intensive operations. Rangelands are typically dominated by grasses and shrubs and occur in non-forested areas that are not suited for farming because limited precipitation and/or tillage is not feasible because of soils or rugged terrain (Lund, 2007; Reeves and Mitchell, 2011). Pastures are often expansive because forage of semi-arid and arid rangelands and forested lands is limited and animals require extensive areas so that they can harvest sufficient forage to be productive. In contrast to intensive operations that house their livestock in barns, pens and small pastures, managers of rangeland livestock operations have difficulty regularly observing their animals (Bailey, 2016). Rangeland livestock operations often use rugged and mountainous terrain with extensive pastures, which limits their ability find and visually observe their animals. Checking the health and well-being of livestock grazing rangelands and forested lands is time consuming, and frequent observation of all the livestock is often not practical and sometime not feasible (Bailey, 2016). The goal of precision livestock management is to provide a real-time monitoring and management system that can improve livestock productivity and welfare. Achieving these goals sustains the operation and allows the farmer or rancher to respond as soon as possible (Berckmans, 2014). For rangeland and forest land livestock operations, precision livestock management may be more beneficial than on intensive operations.

Livestock distribution is one of the four principles of grazing management (Vallentine, 2000), and manipulation of livestock movement patterns is a critical factor for sustainable use of grazing lands by livestock (Bailey, 2004). Managers must monitor the spatial use of rangelands and forested lands by livestock to ensure that areas that are preferred by livestock are not overgrazed (Anderson and Currier, 1973). For example, cattle typically spend a disproportionate time in riparian areas, and this concentrated use can lead to damage to stream banks, fishery habitat degradation and lower water quality (Kauffman and Krueger, 1984; Swanson et al., 2015). Managers have numerous tools to manipulate livestock distribution and resolve concerns of concentrated grazing in riparian areas and other sensitive sites including water developments, fencing, strategic supplement placement, herding, timing of grazing, and use of adapted animals (Williams, 1954; Leonard et al., 1997; Bailey, 2005). Riparian areas often make up a small percentage of semi-arid and mountainous rangelands and forested lands, and excessive forage utilization levels and trampling can occur quickly if managers do not intervene and promptly address undesirable distribution patterns (Wyman et al., 2006). However, the extensive nature of rangeland pastures, woody vegetation, and rugged terrain makes it difficult, time consuming and expensive to visually observe and monitor cattle grazing patterns, especially on a regular basis (Bailey, 2016; Bailey et al., 2018). With the promise of real time or near real time tracking (Bailey et al., 2018), ranchers and graziers can apply precision livestock management to mitigate undesirable grazing distribution and concentrated grazing in riparian areas as well as increase uniformity of grazing in extensive pastures and mountainous topography to improve the efficiency of forage harvest (Bailey et al., 2017). Global positioning systems (GPS) tracking can remotely monitor livestock grazing patterns (Turner et al., 2000), and opposed to store on board (SOB) technology real time tracking can inform managers of grazing distribution concerns as they occur so that they can address the issue as it occurs (Trotter et al., 2010).

The goal of this paper is to describe the potential of precision livestock management to improve livestock welfare and help maintain and enhance rangeland health and sustainability. More specifically, our objectives: are (1) to show how GPS tracking, accelerometers and other sensors to remotely detect livestock disease and other animal wellbeing concerns; (2) discuss the value of monitoring livestock grazing patterns in real time or near real time with GPS tracking and accelerometers to help prevent degradation of riparian areas and other habitats, and (3) describe how data collected from GPS tracking and other sensors must be condensed, transmitted, processed, evaluated and transferred to ranchers and graziers so that they can use these technologies in their day-to-day decision making and management.

Detection of Livestock Welfare Concerns

When livestock become ill, injured, or stressed their day-to-day behavior changes. Animals have predictable diurnal behavior patterns that can be monitored and quantified (Gregorini, 2012). Studies evaluating cattle activity patterns typically show relatively consistent time allocations to given behaviors, but the time spent grazing and in other behaviors can vary from site to site and across seasons. In yearlong studies, Herbel and Nelson (1966) reported that cattle spent 39 to 46% of their time grazing on Chihuahaun Desert rangelands, and Schlecht et al. (2004) found that cows in Germany spent 54–67% of their time grazing. In an Australian study, Kilgour et al. (2012) found that grazing patterns of beef steers varied among five properties within a 140 km diameter area of New South Wales. Behavior patterns can also vary among animals. Gary et al. (1970) observed that cows in the same pasture could have different grazing patterns. To detect changes in behavior patterns associated with disease and other welfare concerns, evaluations of normal vs. abnormal should ideally be conducted on the same animal or at least among contemporaries of animals managed together in the same pasture. For example, current behavior could be compared to diurnal behavior patterns that occurred in the recent past (e.g., the last 7 days).

Remotely Monitoring for Livestock Disease

On rangelands and forest lands, managers must spend a large amount of time and effort to observe the health of their livestock (Bailey, 2016). Pastures are often large and extensive, especially in arid and semi-arid rangelands. Livestock can be difficult to find because of shrubs, trees and rugged topography. Rough terrain and woody vegetation also limit the use of vehicles to travel through the pastures to find livestock. Often there are few roads and paths through rangeland and forest land pastures. Even all-terrain vehicles may not be able to access many areas of wooded and mountainous pastures. Ranchers often use horses to travel through rangeland pastures to find and observe their livestock. Correspondingly, observing livestock in extensive and/or rugged grazing lands is both time consuming and costly.

Accelerometers and other technologies can be used to remotely monitor livestock behavior and have the potential to detect animal welfare concerns including diseases (Bailey et al., 2018). Use of radio frequency identification (RFID) tags and a GrowSafe feeding system was used to successfully monitor cattle feeding in feedlots (Mendes et al., 2011). Hanson and Mo (2014) describe how accelerometers can be used to monitor cow motion and use these data to evaluate the health and well-being of dairy cattle. Accelerometers may be an effective tool to remotely identify fever, lameness and symptoms associated with feeding diseases such as ketosis and displaced abomasums (Helwatkar et al., 2014). Livestock behavior can also be monitored through GPS tracking with or without accelerometers (Augustine and Derner, 2013). Velocity thresholds based on Augustine and Derner (2013) have been used to classify behavior into resting, grazing and traveling by cattle (Nyamuryekung'e et al., 2020).

As livestock become ill, diurnal behavior patterns typically change. For example, calves that have been challenged with *Mannheimia haemolytica* spent less time at the grain bunk and less time at the hay feeder than healthy control calves (Theurer et al., 2013). In the same study, accelerometers successfully identified that bacterially challenged calves spent more time lying than control calves. Hutcheson and Cole (1986) found that healthy calves spent more time feeding than morbid calves during their first week in feedlots in a review of 18 studies. The number feeding bouts of healthy steers was greater than morbid steers during the first month of feeding in a feedlot (Sowell et al., 1999). In addition to changes in activity, livestock may show atypical behaviors and other clinical signs associated with some diseases. Cattle and sheep with experimentally induced rabies had the distinct behavioral signs of infection with increased excitability, aggression, head tremors, and vocalizations (Hudson et al., 1996). Tobin et al. (2020) conducted a proof-of-concept study that showed that accelerometers had the potential to detect diseases such as bovine ephemeral fever in a small pasture setting. Heifer activity dropped during the 24-h period prior to diagnosis of bovine ephemeral fever. The change in activity prior to diagnosis was different from healthy “control” heifers and different from the ill heifer’s previous activity. More research is needed to determine robust algorithms for detecting disease, perhaps specific diseases (García et al., 2020). Also, GPS tracking and other sensors may be useful for detecting disease.

Parturition Detection

Calving and lambing are critical times on rangeland livestock operations. Dystocia, predation, illness and other factors result in early mortality of young livestock (Berger et al., 1992; Bunter et al., 2014; Hinch and Brien, 2014). Advances in development of real-time sensors and GPS tracking provide the potential to remotely monitor for parturition and dystocia which would allow managers to more quickly respond to associated animal welfare concerns (Bailey et al., 2018). During lambing, ewes travel less and separate themselves from the flock, and GPS tracking can identify these behavioral changes and be useful for detecting parturition (Dobos et al., 2014; Fogarty et al., 2020b). In addition, ewes increase the time spent walking, change postures frequently and are generally more restless prior to lambing, which can be identified using accelerometers and used to detect parturition (Fogarty et al., 2020a).

Accelerometers can also be useful for detecting the time of calving (Saint-Dizier and Chastant-Maillard, 2015; Krieger et al., 2019). Miller et al. (2020) reported that accelerometers placed on the tail heads of cows successfully predicted parturition time of beef and dairy cows. Ongoing research in a New Mexico pen study found that, variability of head movements was more useful for detecting lambing than changes in predicted behavior form machine learning. Preliminary results suggested that monitoring changes in an individual’s patterns of movements (accelerometer data) may be more useful than using machine learning to predict behavior and monitoring changes in predictions. Typically, behavioral observations and associated accelerometer data are pooled across multiple animals for machine-learning based predictions. In contrast, monitoring deviations in an individual’s movement patterns could be more useful for detecting well-being concerns, such as parturition. Variability among individuals may reduce the accuracy of machine learning predictions (**Figure 1**), which then limits the value of predicted behaviors for detecting parturition and other important well-being issues. However, much more research is needed to confirm these initial findings.

Fogarty et al. (2021) found that distance that a ewe was from other sheep in the flock was the best metric for remotely detecting lambing. Mean distance from peers (MDP) and this distance relative to the flock’s MDP and distance to the closest peers were all important. These metrics require knowledge of the position of all animals in the herd (**Figure 2**). Surprisingly, the only accelerometer-based metric in the four best indicators of lambing was posture change. The combination of four metrics and machine learning was able to detect up to 91% of lambing events (Fogarty et al., 2021). Detecting the time of calving and lambing would be beneficial for record keeping and providing performance and genetic selection data. However, the largest benefit would be potential to remotely detect dystocia and early calf and lamb mortality.

When dystocia occurs on rangelands and forested lands, both the mother and offspring often die because managers cannot regularly observe all the livestock. Use of real time GPS tracking, accelerometers and other sensors have the potential to reduce the time required to find and assist livestock if dystocia occurs. With real-time GPS tracking and sensors, data can be up-loaded with internet-based tool into a decision-support software system. If the algorithms detect parturition is imminent the manager would be notified with the animal identification, time and location. If the parturition signal from tracking does not change from calving or lambing to post-natal activity patterns in a few hours, there is a good probability there is a problem, and the manager could be sent another message so that someone could be dispatched to check for dystocia.

Water System Failure

Water is most critical nutrient and welfare issue for livestock grazing arid and semi-arid rangelands (Bailey, 2016). Cattle can lose about 7% of their body weight per day if they are deprived of water during the summer and die with 5 days of water deprivation and high temperatures (Siebert and Macfarlane, 1975). Consequently, ranchers usually check livestock water frequently (once every 1–3 days) depending on weather conditions and water storage. Real-time GPS tracking and other sensors have the potential to remotely monitor the availability of water on rangelands. Sensors can be used to monitor water levels in drinkers and storage tanks (e.g., SCADALInk SAT110 livestock monitoring system, Calgary, AB, Canada, https://www.scadalink.com/products/satscada/livestock-water-supply-monitoring/) and the data can be transmitted to ranch headquarters directly or via the internet using mobile phone or satellite technologies (Bailey, 2016; Bailey et al., 2018). Ongoing research in our lab, indicates that on-animal sensors and GPS tracking have the potential to detect water systems failures. Normally cattle do not remain near the water tank after watering and typically move over 100 m from the water tank and rest. During a simulated water failure cattle remained within 100 m of the tank and were

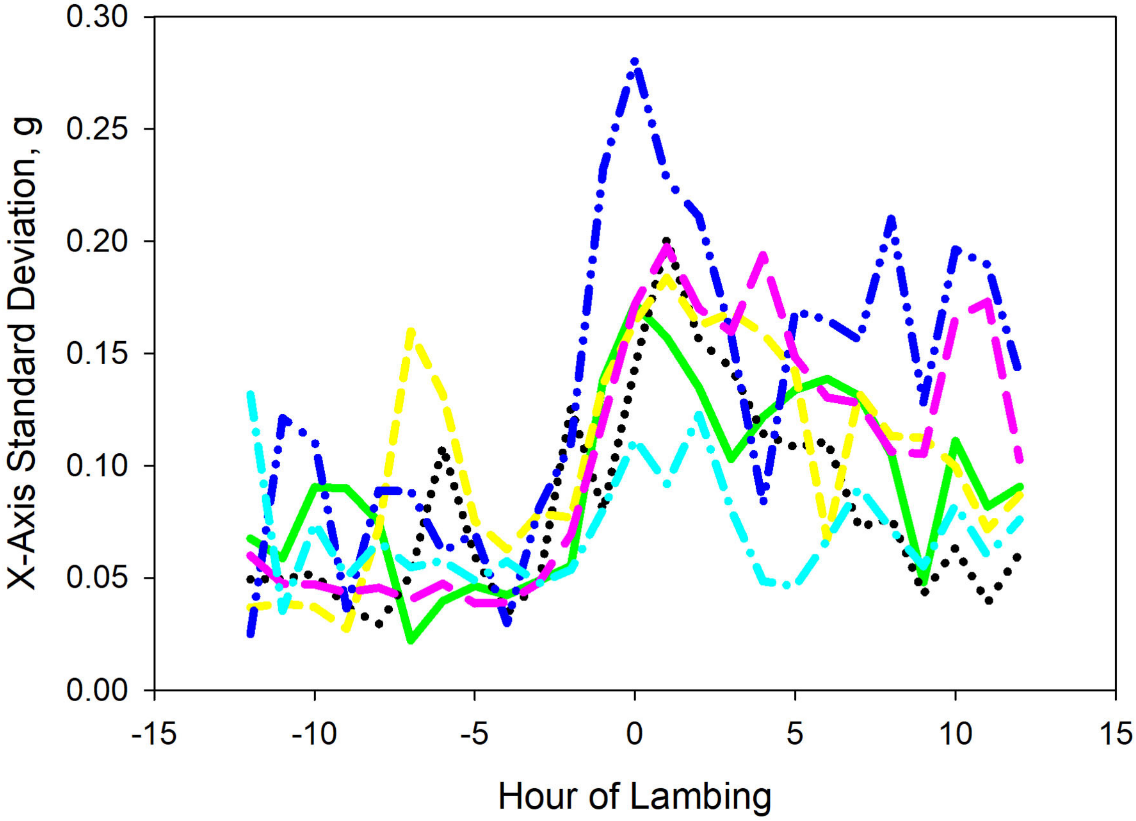

FIGURE 1 | Variability among ewes for an accelerometer-based metric, standard deviation of the *x*-axis (side to side head movements), during the 12 h before and after lambing. Different line types and colors represent the six ewes in the study. Note: the variation in the *x*-axis were relatively low 3–4 h prior to lambing (hour 0), and the variation rises for the period 2 h preceding and 2 h following lambing. However the magnitude of variation differs among ewes.

more active than during normal watering events (**Figure 3**). Normally, cows moved at least 250 m from water after drinking.

Social Interactions and Livestock Well-Being

Cattle, sheep and most other livestock are gregarious animals and social interactions may affect their well-being. Spatial relationships among livestock monitored using GPS tracking and proximity sensors can provide insight into their social relationships (Handcock et al., 2009). Many livestock husbandry practices such as animal purchases and regrouping individuals into different paddocks results in the introduction of unfamiliar animals into a herd. Patison et al. (2010) found that the distance between unfamiliar animals was greater than between familiar animals for several days as the familiarization process progressed. Spatial relationships among cattle is not only an indicator of social interactions but it may be useful for monitoring animal well-being (Patison et al., 2017). Ongoing research in our lab suggests that associations among cattle in rangeland pastures change as forage utilization levels increase. Initially, no differences in association among cows were detected among cows when cattle first started grazing pastures with different stocking densities. Near the end of the grazing (6 weeks) in a smaller pasture (312 ha) with a higher stocking density (0.416 cows/ha), cows were further apart and less associated than in an adjacent but larger pasture (1,096 ha) with a lower stocking density (0.123 cows/ha). Cows in the pasture with a higher stocking density may have spread apart in search of forage as the utilization of palatable grasses increased. Social interactions among livestock may be a tool for monitoring animal well-being.

Managing Predator—Livestock Conflict

Predation can be a critical issue for producers grazing livestock on rangelands and forested lands (Macon, 2020). Predators such as wolves, grizzly bears, mountain lions, wild dogs, and other predators can adversely impact livestock performance as well as injure or kill animals. For examples, cows whose calves have been preyed upon by wolves are more vigilant than cows whose calves were not injured or killed (Kluever et al., 2008). Numerous methods have been used to mitigate the impact of large carnivore predators on livestock including lethal control of predators, herding, fencing, and livestock guardian dogs (Macon et al., 2018; Van Eeden et al., 2018). Livestock guardian dogs (LGD) can be an cost-effective approach to minimize livestock losses to predators if they are effective in reducing losses (Saitone

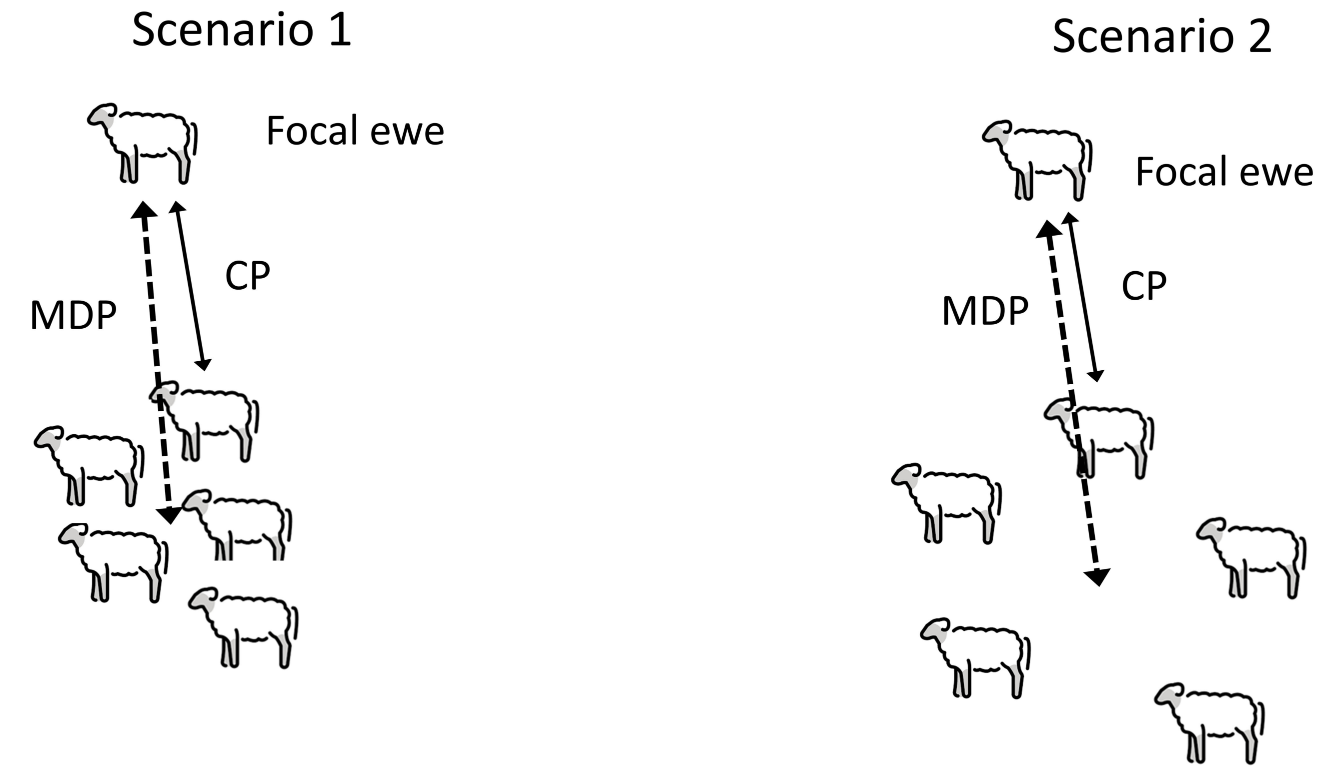

FIGURE 2 | Example of the informative value of considering both the mean distance to peers for the focal ewe (MDP, dashed line) and the average distance from peers of the entire flock. Distance to the closest peer (CP) is one of the important factors for detecting parturition (Fogarty et al., 2021). When the ewe separates from the herd both CP and MDP increase, which is often associated with lambing. However, the signal from MDP and CP is more meaningful in Scenario 1 when the average distance to peers of the entire flock) is relatively low. In contrast, the average distance to peers of the entire flock is larger in Scenario 2 which makes the larger MDP and CP less useful for detecting if the focal ewe is lambing.

and Bruno, 2020). The risk of predation and the nature of livestock and predator spatial interactions can be evaluated using GPS tracking (Clark et al., 2020). Tracking has been used to study spatial interactions of LGD and sheep (Webber et al., 2015; Mosley et al., 2020). As an example, Allen et al. (2017) found that wild dogs entered LGD territory, which suggested that LGD directly protected sheep rather than excluding wild dogs from their territory in Australia. Young et al. (2019) argues that spatial movements of LGD can be used to monitor their effectiveness. The LGD must remain near the sheep to protect them.

Ongoing developments in real time tracking and sensor monitoring have the potential to detect the presence of predators and efficacy of LGD. Changes in spatial movements (tracking) and movement patterns (accelerometers) could be used to alert managers to the presence of predators and allow them to quickly respond. In addition, real-time tracking would allow herders and managers to make sure LGD remain with their herd so that they can protect the sheep. One of the concerns with LGD is to ensure the bonding process is strong enough for the dogs to remain with the sheep. Additional research is needed to develop algorithms and software to use real time on-animal sensors and tracking to detect predator presence and evaluate the efficacy of LGD and other predator mitigation tools.

REAL-TIME MONITORING AND MANAGEMENT OF GRAZING DISTRIBUTION

Many of the sustainability issues associated with livestock grazing are the result of uneven grazing distribution (Bailey, 2004). Livestock tend to congregate in areas with greater forage quantity and quality (Senft et al., 1985; Pinchak et al., 1991), areas that are near water (Valentine, 1947) and areas that take less effort to reach, gentle vs. steep slopes (Mueggler, 1965). Cattle use of riparian areas can impact water quality (Agouridis et al., 2005), and cattle grazing on riparian areas can be a critical issue on public lands (Wyman et al., 2006; Roche et al., 2015). Managers have developed a wide range of management practices that can be used to resolve undesirable grazing distribution patterns (Bailey, 2004) and minimize adverse impacts of livestock on riparian areas (George et al., 2011).

Real-Time Riparian Grazing Management

Livestock grazing management of riparian areas is time sensitive, especially in semi-arid and arid rangelands. Riparian areas typically make up only a small percentage of arid and semi-arid rangelands. For example, riparian areas make up 1–2 %

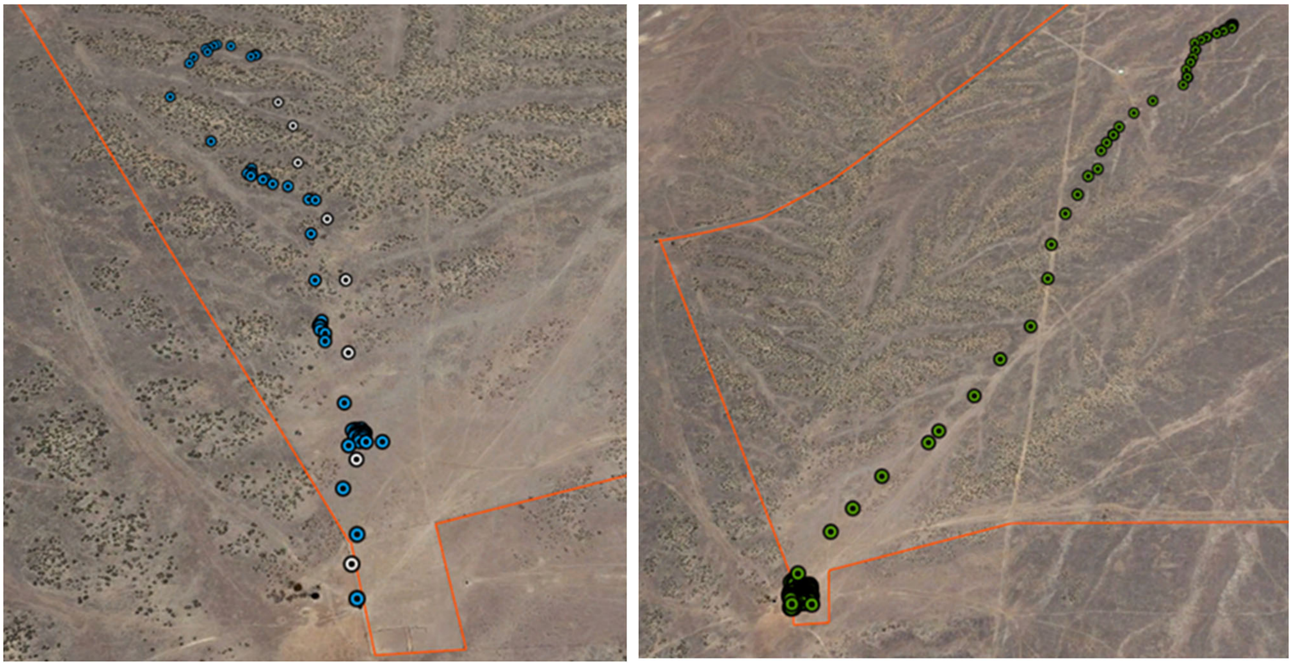

FIGURE 3 | Tracking data of a cow traveling to a water tank, drinking and leaving compared the movement pattern when access to water was denied (simulated water failure). The left map is an example of a normal watering event. White dots on the left graph show a cow walking to water and the blue dots show the cow leaving water. On the right map, the green dots show the cow coming to water and remaining at water during the water system failure simulation. Both maps include tracking that started 30 min. before the cow arrived at the water tank and then an additional hour of tracking.

of rangeland pastures in the Pacific Northwest of the USA (Kauffman and Krueger, 1984). Although they comprise a small areas, riparian areas are essential for maintaining water quality and providing fishery and wildlife habitat (Kauffman and Krueger, 1984) and can potentially produce over 20% of the forage and over 80% of the vegetation intake of cattle during the summer (Roath and Krueger, 1982b). On public lands, managers may ask ranchers to end grazing once stubble heights drop to 10–13 cm (Clary and Leininger, 2000; Tanaka et al., 2007). Cattle are then either moved to a new pasture or moved off the grazing allotment. Low-stress herding and strategic supplement placement can be used to reduce grazing use of riparian areas during the grazing season. Bailey et al. (2008) found that low-stress herding reduced cattle use of riparian areas by 35–50% compared to controls. If GPS tracking could be transmitted in real time, ranchers could monitor cattle grazing patterns and determine if animals concentrate grazing in riparian areas during the grazing season. Such remotely detected information may allow ranchers to implement low- stress herding and other practices to minimize cattle use of riparian areas before the stubble heights drop below the 10–13 cm goal and riparian degradation may begin.

Real-Time Upland Grazing Management

Livestock grazing distribution is a concern for uplands as well as riparian areas. Concentrated grazing can reduce plant vigor and species replacement (Daubenmire, 1940). Eventually, consistent heavy grazing can lead to increased levels of bare ground and active erosion (Blackburn, 1983). Grazing can be heavy in some areas, while other potentially grazeable locations receive little or no use (Norton et al., 2013; Hunt et al., 2014). Grazing distribution practices, such as strategic supplement placement, can improve uniformity of grazing and potentially increase sustainable stocking rates and ranch profitability (Tanaka et al., 2007).

Monitoring livestock grazing distribution on extensive or mountainous rangelands and forested lands is time consuming and expensive with the potential for inaccuracies associated with subjective estimates. Use pattern mapping was designed to measure livestock grazing distribution in an efficient manner (Anderson and Currier, 1973), but this technique relies on subjective observations. Tate et al. (2000) developed a quantitative method of measuring fecal loading on rangelands. Fecal loading can be used to identify areas that cattle use, but it is time consuming to conduct intensive enough measures to assess grazing distribution patterns. In our research, we have measured forage utilization using the height-weight technique at a large number of locations in a pasture to assess grazing distribution (Bailey et al., 2006, 2008). The precision of our lab's approach was dependent on the number of transects measured and the size of the pasture. We used one forage utilization transect for every 3 to 25 ha to assess changes in grazing distribution. Such approaches require time and labor to precisely monitor grazing distribution patterns, and they are not practical for rangeland livestock operations. In addition, vegetation and fecal abundance approaches are typically used at the end of grazing in a pasture to measure grazing patterns, because of the time and effort required for data collection. Use pattern mapping (Anderson and Currier, 1973) can be applied periodically during the grazing period, but the precision and accuracy is dependent on the time spent traversing the pasture and observing vegetation conditions. Ranchers, graziers and land managers typically do not measure use patterns of livestock in a pasture during the grazing period because of the required time and labor.

Remote sensing is another tool to monitor forage conditions on rangelands. Numerous studies have shown the satellite and unmanned aerial vehicles (UAV) can provide imagery to estimate spatial and temporal changes in forage production (Reinermann et al., 2020). Indices such as the normalized difference vegetation index (NDVI) can identify spatial variation in vegetation availability associated with different grazing systems (Blanco et al., 2009) and spatial changes in forage abundance that occur at varying distances to water and with uneven livestock grazing distribution (Blanco et al., 2008). Spatial maps of forage productivity derived from satellite and UAV imagers could help managers determine pastures with greater forage abundance throughout the year (Reinermann et al., 2020). Although forage quantity is clearly an important determinant of livestock grazing patterns, forage quality is often more important (Senft et al., 1985; Pinchak et al., 1991). Livestock are attracted to areas of with higher levels of crude protein and digestibility (Bailey, 2005). Satellite and UAV imagery can remotely monitor spatial and temporal changes in forage quality (Thoma et al., 2002; Lugassi et al., 2019; Wijesingha et al., 2020). Mapping spatial and temporal changes in forage quality could be used to determine pastures where there has been recent precipitation and livestock performance should be higher (Trotter, 2010). Such maps would also allow managers to identify areas that have higher forage quality and would be preferred by livestock (e.g., riparian areas) and allow them to focus monitoring efforts to ensure preferred sites are not overgrazed. In addition, remote sensing can be helpful in monitoring the long term benefits for grazing management practices such as water developments and fencing (Rigge et al., 2014).

Global positioning system tracking provides an accurate and quantitative method to assess livestock movement patterns in pastures (Bailey et al., 2018). Recently, the cost of GPS tracking collars have decreased (Knight et al., 2018; Karl and Sprinkle, 2019) so that ranchers may be able to afford to use them to remotely monitor cattle movements. Millward et al. (2020) describe how GPS tracking data could be used to adjust stocking rates based on grazing distribution patterns similar to the approach developed by Holechek (1988) to account for areas that cattle may avoid due to long distances from water and steep slopes. Although GPS tracking clearly shows livestock movements, GPS tracking data does not necessarily reflect patterns in forage utilization (Millward et al., 2020). In Montana studies, GPS tracking data showed similar grazing distribution patterns as height-weight forage utilization transects measured at multiple locations across the study pastures (Bailey et al., 2006, 2008; Bailey and Jensen, 2008). More research is needed to verify that GPS tracking accurately reflects the spatial variation in forage use across pastures.

Genetic Selection for Distribution Using GPS Tracking

Individual beef cows and likely other livestock express different grazing patterns especially in expansive pastures and rugged terrain. For example, Bailey et al. (2004) reported that cows that used steeper slopes the previous year (hill climbers) spent twice as much time on steep slopes (44–57% slope) as cows that used gentler terrain the previous year. Hill climber cows were also 46 m higher in average elevation use than the bottom dweller cows. Several researchers have suggested that selection could be used to take advantage of the variation in spatial grazing patterns of cattle and that ranchers could cull cows that prefer gentler terrain near water and retain cows that use steep terrain and areas far from water (Roath and Krueger, 1982a; Howery et al., 1996; Bailey et al., 1998). Selecting cows that use more rugged terrain (hill climbers) and culling cows that prefer gentle terrain near water (bottom dwellers) has the potential to increase the uniformity of grazing (Bailey et al., 2006). In this Montana study, pastures grazed by hill climbers had more grazing on steep slopes and less use of gentle terrain near water than pastures grazed by bottom dwellers. Stubble heights in riparian areas averaged in pastures grazed by hill climber cows was 13 cm, which is above the recommend riparian stubble height of 10 cm (Clary and Leininger, 2000), and 8 cm in pastures grazed by bottom dwellers.

Selection can potentially modify livestock behavioral patterns through both nature and nature (Bailey and Provenza, 2008; Provenza, 2008). Heifers tend to graze the same areas as their mothers graze (Howery et al., 1996). In a cross-fostering study, Howery et al. (1998) demonstrated that the mother's impact on their heifer's grazing patterns could be at least partially attributed learning rather than inheritance alone. Two studies identified that cattle grazing patterns (terrain use traits) were associated with single nucleotide polymorphism (SNP) genetic markers (Bailey et al., 2015; Pierce et al., 2020). The associations between terrain use traits (e.g., slope use and distance traveled from water) and multiple SNP shows that spatial movement patterns are heritable and that these traits are affected by multiple genes; therefore, are polygenic (Pierce et al., 2020). The candidate genes for grazing traits were also associated with other cattle traits such as heat stress, oxygen homeostasis, feed efficiency and growth. Two Montana studies showed that there were no adverse phenotypic correlations between terrain use traits and cow performance traits (Bailey et al., 2001; VanWagoner et al., 2006). Correlations between terrain use traits (slope use and vertical and horizontal distance traveled from water) and cow body condition score, calf weaning weight, calving date and hip height were generally low (between −0.2 and 0.2) and inconsistent among years.

More research is needed to develop genetic selection tools for grazing distribution. The biggest limitation has been the cost of measuring grazing distribution. Initially, we used horseback observers to record cattle locations during their morning grazing bouts (Bailey et al., 2006). Several observers were needed to locate up to 180 cows in 100–350 ha pastures during 1.5–2.5 hour period. The labor cost with this approach would be prohibitive for most ranches. The cost for GPS tracking collars was over $4,000 when cattle were first being tracked in the late 1990's

(Anderson et al., 2013). Today, GPS collars can be built and purchased for less than $250 (Knight et al., 2018; Karl and Sprinkle, 2019). Even lower cost GPS units are being designed and tested. If real-time GPS tracking tags are used to monitor livestock health and well-being, another benefit would be the ability to document terrain use preferences of individual cows.

Another potential approach to monitor livestock terrain use traits and distribution patterns is through aerial photography using drones or small aircraft (Thomas et al., 2020). A bar code or similar visual identification could be glued or attached to the cattle's backs. High definition cameras could read the animal identification and geoposition cattle location using a GPS on the drone or plane. One limitation of this proposed methodology is that the pastures must relatively open with only a few areas of woody vegetation so that the cattle would readily visible from above. This approach has not been fully developed and tested, but it may be a relatively low cost method for monitoring spatial patterns of grazing cattle in rangelands dominated by grasses and forbs.

The identification of genetic markers for grazing distribution traits reduces the need to track cows for quantifying the terrain use phenotype. To make progress using genetic selection, it is most critical to select sires that have superior genotypes for the desired trait. The most progress can be made through bull selection, as opposed to culling inferior cows or selecting superior replacement females (Bourdon, 2000). The selection differential for bulls is much greater than for replacement heifers or culling inferior cows. Unfortunately, it is difficult to accurately assess the terrain use phenotype of bulls. During the breeding season, bull libido likely affects their spatial movements more than tendencies to travel for forage. Outside of the breeding season, bulls are typically kept together in the same pasture. The number of bulls is often <40 in all but large operations. Stephenson et al. (2016) reported that groups of 40 or less cattle tended to stay together, which limits animal's willingness to express differences in individual movement patterns. With the identification of genetic markers and candidate genes for terrain use, genomic breeding values can be developed. Genomic breeding values are a useful selection approach for hard to measure traits such as terrain use (Eggen, 2012). Genomic breeding values use single nucleotide polymorphisms or other genetic markers to estimate an individual's breeding value for the trait. Deoxyribonucleic acid (DNA) samples could be obtained from bulls and replacement females and processed for the appropriate genetic markers (i.e., genotypes). Bulls and replacement heifers could then be ranked for their potential to improve terrain use using their genomic breeding values. However, it must be acknowledged that genetic evaluation, with or without assistance of genomics, to estimate breeding values and their accuracies requires large scale data collection with ample number of contemporary group comparisons of familially-related animals; therefore, improvement in data acquisition technologies for tracking large numbers of cows is needed to help develop strong genetic improvement programs.

Another factor that is hindering development of breeding values for terrain use of beef cattle is that topography, water locations, vegetation types and forage quantity and quality vary tremendously among pastures, both spatially (terrain and water location) and temporally (forage quantity and quality). The impact of slope and horizontal and vertical distance to water on cattle grazing patterns is complex and nonlinear (Bailey, 2005). For example, steep slopes have less impact if they are located close to water compared to the effect of steep slopes at locations far from water (Mueggler, 1965). The variation in terrain among pastures and locations makes it difficult to quantify the effort cattle incur climbing steep slopes, traveling long distance to water and reaching high elevations. Pierce et al. (2020) concluded that this variability associated with topographic complexity contributed to the low proportion of genetic variation in grazing distribution explained by quantitative trait loci (SNP genetic markers). Tools such as resource selection functions (Nielson and Sawyer, 2013) and topographic indices (Gersie et al., 2019) may be useful for comparing grazing patterns across pastures and adjusting to the variability associated with terrain and water locations. Bailey et al. (2015) developed indices using ratios in an attempt to integrate the impacts of slope, elevation and horizontal distance to water. These indices normalized the values of topographic metrics (slope, distance to water and elevation) by dividing by the mean and multiplying by 100 and then averaged the metrics which weighted them equally. However, ongoing research shows that the impacts of slope and vertical and horizontal distance from water varies on cattle distribution is different for each pasture. The coefficients of resource selection functions may be a good tool for weighting the impact of topographic variables on cattle distribution if the topographic metrics are scaled (e.g., feature scaling). Rather than using equal weight for slope, elevation and distance to water the coefficients could be applied to scaled terrain metrics to produce an index that should be more comparable from one pasture to another. Gersie et al. (2019) found that topographic position classes (TPC) could be used to predict cattle distribution on multiple short grass prairie pastures. Use of TPC or similar terrain classifications may be another alternative to quantify the effort to use rugged and extensive rangeland pastures by individual cows across multiple locations.

Virtual Fencing

Virtual fencing is a tool to enclose and control livestock without ground-based traditional fencing (Anderson, 2007). Recent systems use GPS receivers to track the animal, GIS algorithms to establish boundaries, radio frequencies to communicated with managers, sound cues to alert animals of approaching boundaries and mild electric shock to discourage animals from crossing boundaries (Campbell et al., 2017). Virtual boundaries can be placed in any location and easily moved to exclude animals from environmentally sensitive areas, modify stocking density, implement rotational grazing systems and modify grazing distribution patterns (Anderson et al., 2014). Campbell et al. (2019a) demonstrated that virtually fencing could be used to exclude cattle from riparian areas. Cattle quickly learn to avoid excluded areas and this learning can be facilitated through social interactions (Keshavarzi et al., 2020). However, Markus (2002) found that cattle with inactive devices readily crossed virtual boundaries and cattle while active devices did not enter excluded areas during simulated equipment failures. Virtual fencing systems have promise to control livestock movements, but the cost of the devices compared to traditional fencing may limit adoption by rangeland livestock producers (Banhazi et al., 2012; Umstatter et al., 2015). In addition, the public may have concerns with virtual fencing (Stampa et al., 2020). For example, Markus et al. (2014) found that cattle avoided an excluded area days after the virtual fencing system was discontinued, while cattle readily entered the excluded area when electric fencing was dismantled. In contrast, Campbell et al. (2019b) found that fecal cortisone levels were similar for cattle constrained virtual fencing and traditional electric fencing. Virtual fencing may become a prominent tool in precision livestock management if educational programs are developed to address public concerns with the welfare of livestock constrained by virtual fencing (Stampa et al., 2020), and the cost of virtual fencing equipment drops to a level comparable to labor, material and maintenance costs of traditional fencing.

DATA PROCESSING AND TRANSFER

Currently, most low-cost GPS collars store the tracking data on the collar (store on board, SOB), and the cattle must be gathered and placed in corrals so that the collars can be retrieved. The SOB tracking equipment does not allow managers to remotely monitor livestock distribution or animal behavior in real-time or near real time. This is a major limitation because managers can use GPS tracking to remotely monitor livestock health and well-being or spatial distribution pasterns when grazing is occurring in a pasture and respond when concerns or opportunities arise. Precision livestock management monitoring with SOB technology is only useful for proof of concept, algorithm development and simulated well-being issues. Real-time tracking is critical to assess changes in animal movements, spatial distribution and behavior that could detect animal health and welfare concerns. In addition, development of real time or near real time GPS tracking may allow managers to identify issues with livestock spatial distribution, implement management practices while the pasture is grazed and monitor the success of the management interventions (Bailey et al., 2018). Smartbow (Zoetis, Weibern, Austria) has a real-time tracking system for dairy cows (Wolfger et al., 2017). Moovement (Brisbane, QLD, Australia, https://www.moovement.com.au) have developed a commercially available GPS ear tag that records animal position every hour and transmits this data to a LoRa (Long Range) antenna (Sanchez-Iborra et al., 2018) and then it is forwarded to the internet using cellular phone technology. The ear tags are designed to transmit data from the ear tag 8 km (line of sight) to the LoRa antenna. The Moovement system also contains an iPhone application (app) that allows ranchers and graziers the opportunity to see the most recent location of tracked cattle. This Moovement app uses Google Earth imagery for visualizing cattle locations. Other companies are developing real-time and near real-time GPS tracking systems for livestock grazing rangeland, but their products are not currently commercially available (**Table 1**).

Currently, most commercially accelerometers produce massive amounts of data, because they record movement (acceleration) of three axes at 12–25 Hz. Transferring such large amounts of data in real time or near real time is prohibitive for livestock grazing rangeland because of the battery demand for transmission. To reduce the size of the transmission from the sensor (e.g., accelerometer), data must be processed and summarized. The process of analyzing and processing sensor data on the device is termed "edge computing" or "front end processing" (Habib ur Rehman et al., 2016, 2017). Cheng et al. (2014) used a locally sensitive Bloom filter to reduce the size of sensor data. Edge computing can use historic data and machine learning processes (García et al., 2020) such as random forests and signal vector machine to detect important states or events from data streams obtained from sensors (Park et al., 2018). Hu et al. (2016) demonstrated that edge computing reduced response time and energy use of mobile devices. For livestock, sensors must be small and large batteries are not practical, especially for ear tag sensors. Ear tag sensors are preferred by ranchers and graziers and are a reliable location for monitoring activity using accelerometers (Barwick et al., 2018). Herddogg (https://www.herddogg.com/) is developing a commercially available ear tag with an accelerometer to monitor livestock health and well-being. Data from the ear tag are transferred from the tag to a reader using blue tooth technology when the animal approaches the reader which is placed in a frequently visited location (e.g., water). Herddogg tri-axial accelerometer readings recorded at 24 Hz are compressed to a single value every 6 min. This reduces the size of transferred data and minimizes battery consumption.

Algorithms that are used to detect illness, well-being issues, spatial distribution concerns and other problems from real-time streams of location, accelerometer and other sensors must be developed and evaluated using experimental and on-ranch studies. Scientists addressing precision livestock management will be critical part of this research. We advocate for increased levels of research in this area of study and encourage interdisciplinary approaches with animal and range scientists working with computer scientists and electrical engineers.

Ideally, precision livestock management systems will include all the mature livestock on a ranch and perhaps even offspring. Monitoring and tracking all livestock maximizes opportunities to identify issues and concerns with individual animals and those for the herd. However, this may not be economically feasible because of equipment cost and subscriptions for transmitting data to the internet. For example, some systems rely on subscriptions for satellite data transfer. A less costly alternative (sentinel animals) relies on a limited number of remotely monitored livestock (Neo and Tan, 2017). Sentinel animals and sentinel herds are commonly used to monitor the occurrence of diseases such as blue tongue virus (Giovannini et al., 2004). For precision livestock management, tracking and monitoring sentinel animals would be helpful for monitoring the overall health of the herd, but not individual animals. Correspondingly, it would not be useful for detecting parturition or to identify animals that require treatment for an illness. However, sentinel

TABLE 1 | Non-exhaustive listing of companies that have developed or are developing on-animal, real-time or near-real time tracking and sensors for livestock grazing rangelands.

Company	Country	Device	Type	Real or near time	Data transmission	Status	Website
Moovement	Australia	GPS tracking	Tag	Real	LoRa and cell phone	Available	https://www.moovement.com.au/
Moonitor	Israel	GPS tracking/accelerometer	Collar	Real	Satellite	Available	https://www.moonitorcows.com/
Smart Paddock	Australia	GPS tracking	Collar or tag	Real	LoRa	Available	http://smartpaddock.com/
Digital Matters Oyster 2	USA	GPS tracking	Attach device to collar	Real	Cell phone	Available	https://www.digitalmatter.com/devices/oyster2/
Smarter Technologies	UK	GPS tracking	Collar	Real	Orion Network	Available	https://smartertechnologies.com/smarter-products/gps-cattle-collar/
Cattle Watch	South Africa	GPS tracking/ccelerometer	Collar and tag	Real	Satellite or cell phone	Available	http://www.cattlewatch.co.za/
CeresTag	Australia	GPS tracking	Tag	Real	Satellite	Development	https://www.cerestag.com/
AeXonis	USA	GPS tracking	Tag			Development	
Herddogg	USA	Accelerometer/thermometer	Tag	Near real	Blue tooth	Development	https://www.herddogg.com/
Alflex/SCR	Israel	Accelerometer	Collar and ear tag	Real	Proprietary	Available	https://www.allflex.global/au/product/sensehub-for-beef/
Quantified AG	USA	Accelerometer/thermometer	Tag		LoRa	Development	https://quantifiedag.com/

animal tracking could potentially be used to help detect water system failure and spatial distribution issues. If sentinel animals spent more time at a water tank, it would be likely that there is a problem with the water system. Similarly, if sentinel animals concentrate in an environmentally sensitive area of a pasture, this would be an indication of potential over grazing and resource degradation.

CONCLUSIONS

Development of real-time and near-time tracking has facilitated the development of precision livestock management, which can allow managers to remotely monitor livestock health and well-being. Real-time tracking could also monitor spatial movement patterns of livestock and potentially identify areas where animals are concentrated and may be overgrazing and causing resource degradation. Algorithms in precision livestock management system would detect animal well-being issues and resource concerns, and the manager would be notified and could respond as soon as possible. Ongoing research is providing proof of concepts of the value of real-time tracking and monitoring. Accelerometers can remotely monitor the decrease in activity associated with the onset of illness. Real-time GPS tracking is an on-animal sensor method for detecting water system failures. The combination of GPS tracking of all ewes and accelerometer monitoring provides an accurate method for detecting the onset of lambing. The identification of genetic markers that are associated with terrain use demonstrate that grazing distribution traits are inherited. New uses for GPS tracking and evaluations of novel processing approaches using geographical information systems and resource selection functions may facilitate development of genetic selection tools for terrain use of beef cattle. To develop these genetic tools, collection of data from large numbers of cattle is also needed. Precision livestock management is an exciting new field of study that has potential to reduce labor costs, enhance livestock well-being and improve the economic and environmental sustainability of rangeland livestock operations.

AUTHOR CONTRIBUTIONS

DB prepared the initial draft. All authors contributed to the research and analyses used in the development of this paper. All authors edited and improved the paper.

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REVIEW
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Red Chittagong Cattle: An Indigenous Breed to Help Tackle the Challenges of Modern Animal Production Systems

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Modern livestock selection is rapidly condensing the indigenous cattle gene pool. This trend limits the options for future genetic selection to benefit both animal well-being and farmer challenges. Here we reveal the potential of Red Chittagong cattle (RCC), a native genotype of Bangladesh, for tackling these current and pending challenges. Red Chittagong cattle are reddish in color and small in size with mature bulls and cows weighing 342 and 180 kg from birth weights of 16 and 14 kg, respectively. Whilst low mean levels of milk production of 618 L across a 228-day lactation are recorded so are high levels of milk protein (3.8%) and fat (4.8%) with offered feed types typically low in nutritive value, particularly crude protein. However, one in five cows under farm condition yield >1,000 L/lactation. Alongside high levels of milk protein and fat, other key features of this breed include resistance to common diseases and parasites with a high level of adaptation to agro-ecological conditions. As opposed to other indigenous breeds, there is currently high genetic variation in the RCC population, and associated variation in productive and reproductive traits highlighting the opportunity for development through long-term breeding programs alongside improved management conditions. Such efforts would enable this breed to become a global resource for tackling the challenges of modern animal production systems. In addition, further work is required to reveal the demographic distribution of the breed, potential production levels through the provision of improved diets and the mechanisms enabling disease resistance and digestibility of feeds.

Keywords: Bangladesh, genetic variation, heritability, milk production, morphology, origin and distribution

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INTRODUCTION

The transition of agriculture from the Neolithic age to the intensive commercial systems of today helps ensure food security and better standards of living for the growing global population (Silbergeld, 2019). In many commercial animal production systems around the world, high producing animals of similar genotypes are typically reared in confined housing systems with mechanically processed feedstuff. Recently, farms in Bangladesh have introduced Holstein genetics into more intensive systems from Australia and the Netherlands. Such high producing animal genotypes are reared to achieve high productivity and profitability, largely omitting native animal genotypes which threatens their survival as a breed. Moreover, such intensification may increase the risk of disease transmission both between animals, and animal-to-human, alongside antibiotic resistance (Leibler et al., 2017; Aidara-Kane et al., 2018). Therefore, long term sustainability of intensive livestock production using commercial breeds, which mostly developed in the temperate countries, is questionable especially under tropical climatic condition. In contrast, native livestock resources in tropical countries evolved through natural selection based on the phenotype characteristics and organoleptic evaluation (tastes of products) preferred by the native consumers whilst these local breeds are typically adapted to prevailing hot and humid climates, locally available feeds, are resistant to parasitic and diseases, and have a greater survival rate, giving birth to a calf every year (i.e., more fertile). For example, Khan et al. (2012) reported the profitability of rearing crossbred dairy cows in Bangladesh (Holstein × Indigenous cattle) was less than native Red Chittagong Cattle (RCC) on a lifetime productive performance basis. Also, indigenous cattle genetic resources are usually resistant to some parasites, disease infections and environmental stress in their natural habitats (Nyamushamba et al., 2017). Therefore, maintaining an improved balance between intensification of commercial genotypes (mainly Holstein and their crossbreds/hybrids that are frequently reared in commercial farms) and the extension of high producing local genotypes may help ensure food and nutrition security and improve health of local communities by keeping antibiotic resistance of animals and reducing community disease transmission into the future. In this context, this review will focus on the native Red Chittagong cattle (RCC) breed of Bangladesh—a breed developed under highly challenging environmental conditions.

The name "Red Chittagong" cattle is derived from the breed's reddish coat color (Huque et al., 2010; Bhuiyan, 2013; Sultana, 2018) and the name of its natural breeding habitat—Chittagong, Bangladesh. Red Chittagong cattle are regarded as an improved native cattle species in Bangladesh (Mason and Buvanendran, 1982; Mason, 1988). Other improved native cattle genotypes found in Bangladesh are Pabna cattle at Pabna region, North Bengal Gray at Northern region, and Munshigonj and Madaripur cattle of Central Bangladesh (BLRI, 2004; Bhuiyan et al., 2005; Hossain, 2005; Bhuiyan, 2013; Sultana, 2018). Red Chittagong cattle are a dual-purpose breed for dairy and beef production and play a key role in poverty alleviation for small holder farmers in its habitat (BLRI, 2004). The breed also has a short post-partum heat period, high conception rates, greater milk fat content (Halim et al., 2010; Bhuiyan, 2013) and high calving rate (Khan et al., 2012). In addition, the breed is more resistant to parasites and diseases prevailing in its habitats than other cattle (Ahmed et al., 2015; Chowdhury et al., 2017) with high survivability in both adults and calves (Quaderi et al., 2013). A life-time economic evaluation of different dairy cattle breeds conducted in the rural areas of Chittagong reported greater profitability of rearing RCC compared to other cattle genotypes (Khan et al., 2012). Considering these attributes, RCC may be regarded as a potential cattle genotype to tackle the future challenges of intensive animal production in Bangladesh. Therefore, the objectives of this review were to synthesize existing research knowledge of the RCC breed and reveal the potential of this breed to tackle the challenges of our modern animal production systems whilst highlighting the opportunities for future research. A review of Red Chittagong cattle distribution, genotype and the interaction of this genotype with the environment (phenotype) are provided here.

TABLE 1 | Number of Red Chittagong cattle at Chittagong, Bangladesh (2008).

Regions	TCN	RCC (%)	RCC (heads, calculated)
Anowara	24,624	9.87	2,430
Chandanaish	28,348	35.42	10,040
Raozan	40,578	19.98	8,106
Potiya	30,586	8.83	2,699
Boalkhali	10,418	14.51	1,512
Satkania	47,082	8.77	4,131
Lohagora	38,374	6.32	2,427
Banshkhali	49,625	5.26	2,610
Rangunia	48,762	1.57	768
Hathazari	26,447	13.48	3,564
Fatikchhari	85,160	1.84	1,570
Sitakunda	29,616	5.52	1,634
Total	459,620	-	41,730

TCN, total cattle number in 2008 (BBS, 2011); RCC (%), Red Chittagong cattle (Huque et al., 2010); RCC (heads), calculates as TCN × $\frac{RCC\ (\%)}{100}$.

THE DISTRIBUTION OF RED CHITTAGONG CATTLE

The main habitat of RCC is in Chittagong. A survey conducted a decade ago (2008) in Chittagong found only 9% cattle were RCC ranging from 2% in the Rangunia region to 35% in Chandanaish (**Table 1** and **Figure 1**) (Huque et al., 2010). Anecdotally, the number of RCC was decreasing due to indiscriminate crossbreeding with Holstein and other native cattle, presumably because of a common conception that crossbreds of native cattle with high-yielding breeds will produce more meat and milk, ignoring potentiality of lifetime productivity and profitability from RCC. Given these dwindling numbers, the Bangladesh Government took the initiative to protect this RCC in its habitat and develop the breed to help ensure its survival (RCC breed Improvement and Conservation Project, implemented by Bangladesh Livestock Research Institute during 2007–2012).

The impact of this government intervention is evident as per a recent survey (BSR, 2018) taken from six administrative regions of Chittagong (Anowara, Banskhali, Chandanaish, Hathazari, Patiya, and Satkania) that showed 15% of the total cattle population to be RCC. More importantly, this survey showed RCC was spreading throughout the country in the districts neighboring Chittagong such as Feni, Noakhali, Comilla, Rangamati, Bandarban, Khagrachori to as north as Mymensingh and Kurigram (Huque et al., 2010; Hamid et al., 2017; BSR,

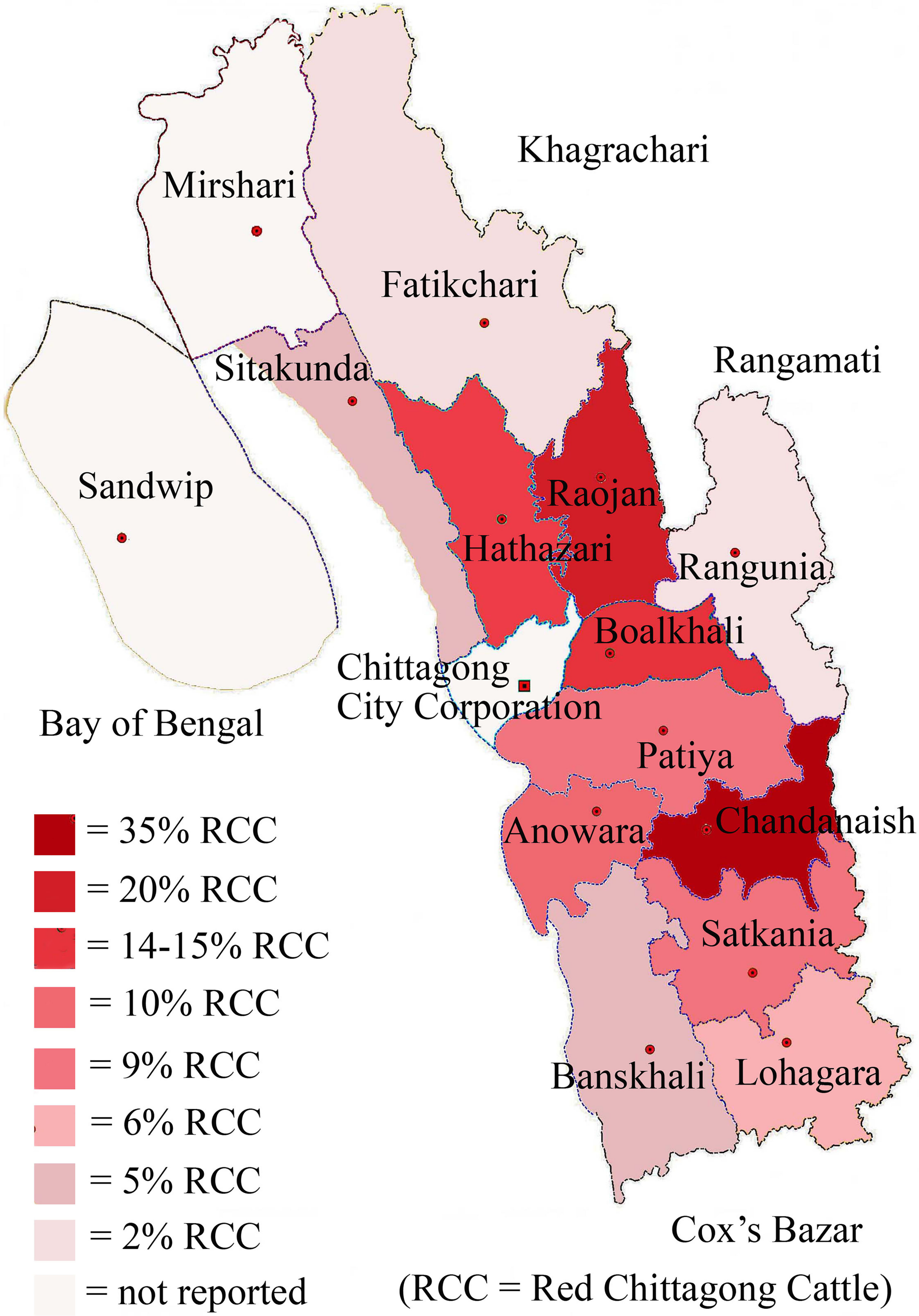

FIGURE 1 | Geographical distribution of Red Chittagong cattle at Chittagong in 2008 [adapted from Huque et al. (2010)].

2018). BSR (2018) in a recent survey reported 58% of cattle in Mymensingh sadar, 7% in Kurigram (Rajarhat) and 4% cattle in Bandarban (Naikhongchari) were RCC. Thus, a detailed survey is required to document RCC number and distribution across the country, including its impact on farmers to further steps to protect RCC and improve the breed through the genetic selection process.

GENOTYPE

The origin of the RCC breed is closely linked to Indian zebu cattle genotypes (*Bos indicus* sub species). Bhuiyan et al. (2007a) reported that the mitochondrial DNA diversity between RCC and some zebu cattle (Ongole, Sahiwal, Hariana) was lower than the diversity between RCC and some taurine breeds (Friesian and Simmental). The minimum mitochondrial-DNA nucleotide sequence divergence value between RCC and Indian zebu cattle (Sahiwal, Hariana, and Ongole cattle; 0.011, 0.012, and 0.013, respectively) compared to some taurine cattle (Friesian, Hanwoo, and Simmental; 0.054, 0.055, and 0.056, respectively) indicates a close genetic relationship between RCC and Indian zebu cattle (Bhuiyan et al., 2007a), particularly between RCC and Sahiwal. When mitochondrial-DNA nucleotide sequence divergence value was viewed across time between RCC vs. Sahiwal, Hariana, and Ongole cattle, the estimated divergence time were ∼22,700, 24,800, and 26,900 years before present (Bhuiyan et al., 2007a),

TABLE 2 | Heritability estimates of some productive traits of Red Chittagong cattle.

Productive traits	Heritability	*SD*	*N*	Minimum	Maximum	Total cattle observation
Birth weight	0.47	0.02	4	0.45	0.49	419
Weaning weight	0.48	0.01	3	0.47	0.49	401
Lactation length	0.44	0.05	3	0.39	0.47	330
Lactation milk yield	0.38	0.09	4	0.27	0.47	380
Pre-weaning gain	0.47	0.04	4	0.41	0.50	528
Post-weaning gain	0.49	0.00	2	0.49	0.49	288

SD, standard deviation; N, number of articles that reported the parameters. From Afroz et al. (2011), Afroz et al. (2012), Alam et al. (2007), Ferdous et al. (2019), Rabeya et al. (2009), and Rahman et al. (2016).

FIGURE 2 | Red Chittagong cattle of Bangladesh.

suggesting their concurrent emergence long before the time of animal domestication (about 10,000 years). The Y-chromosome specific marker test (INRA-124) also showed no introgression of taurine blood in the RCC male (Bhuiyan et al., 2007a).

Whilst natural selection played a key role in the evolution of RCC, human activity also contributed to shaping the breed such as reddish coat color and strong and stout physical conformation suitable for draft and transport (Bhuiyan et al., 2008; Bag et al., 2010). These characteristics were also in line with the needs of rural farmers and their religious and social rituals, as a mature healthy bull with attractive red color is important for sacrifice during different religious events (such as, Eid al-Adha).

Bhuiyan et al. (2007a) reported a high genetic variation of this breed within the population using mitochondrial DNA sequence

TABLE 3 | Physical appearance of Red Chittagong cattle.

Body part	Color	%	Other descriptions
Body	-	-	The body is blocky. Male is heavier than female.
Physical condition	-	-	They are strong and stout in physical condition.
Head	-	-	Head is narrow and thin with flat forehead.
Hump	-	-	Hump is well-developed and vertically erected. It is more prominent in male than female.
Legs			Legs are medium, firmly set under the body and well-apart from one another.
Ears	-	-	Ears are medium in size, alert and slightly dropping.
Coat color	Reddish	78	The hair coat is fine, short, strong and smooth with remarkable shine.
	Reddish-yellow	13	
	Reddish-white	9	
Horns	Reddish-black	94	Horns are medium and stumpy, tapering to a blunt point.
	Whitish	6	
Muzzle	Reddish	65	-
	Whitish-red	35	
Hoof	Reddish	78	-
	Pale red	12	
Eye ball	Reddish	98	-
	Blackish-red	2	
Eye brow	Reddish	100	-
Vulva	Reddish	100	-
Switch	Reddish	100	-

From Bag et al. (2010) and Bhuiyan et al. (2008).

TABLE 4 | Physical measurements of mature Red Chittagong cattle.

Parameters (cm)	Male					Female					Total cattle observation
	Average	*SD*	*N*	Min	Max	Average	*SD*	*N*	Min	Max	
Length (shoulder to pin bone)	132	3	2	130	134	111	5	2	107	114	70
Wither height	125	1	2	124	125	107	1	2	106	108	70
Heart girth	147	13	2	137	156	123	25	2	105	140	70
Horn length	12		1	-	-	11	-	1	-	-	50
Horn diameter	12		1	-	-	9	-	1	-	-	50
Teat length	-	-	-	-	-	5	-	1	-	-	50
Teat diameter	-	-	-	-	-	6	-	1	-	-	50
Distance between fore teats	-	-	-	-	-	7	-	1	-	-	50
Distance between rear teats	-	-	-	-	-	6	-	1	-	-	50
Regardless of sex											
Ear length	16		1			-	-	-	-	-	50
Ear width	12		1			-	-	-	-	-	50
Tail with switch	92		1			-	-	-	-	-	50

SD, standard deviation; N, number of articles that reported the parameters; Min, minimum; Max, maximum.
From Bag et al. (2010) and Habib et al. (2003).

TABLE 5 | Productive and reproductive traits of Red Chittagong cattle.

Parameters	Average	*SD*	*N*	Minimum	Maximum	Total cattle observation
Birth weight of male calf, kg	16	0.9	6	14	16	659
Birth weight of female calf, kg	14	0.8	6	12	15	659
Weaning age, months	8	1	4	7	9	293
Weaning weight, kg	53	5.3	8	48	65	420
Mature weight of male animal, kg	342	70	4	268	436	147
Mature weight of female animal, kg	180	14	4	160	191	721
Age at puberty of male calf, months	25	-	1	-	-	27
Age at puberty of female calf, months	29	4	19	15	33	163
Gestation period, days	283	3	23	279	287	1,742
Age at first calving, months	41	3	11	34	45	754
Post-partum estrous, days	96	33	21	40	141	1,163
Calving interval, months	14	1	26	12	15	1,978
Conception rate of cows, %	78	-	1	-	-	95
Service per conception	1.5	0.2	31	1.2	1.8	1,757
Calf survivability, %	94	2	4	93	97	1,348

SD, standard deviation; N, number of articles that reported the parameters. From Afroz et al. (2011), Alam et al. (2007), Amin et al. (2013), Asaduzzaman et al. (2017a), Asaduzzaman et al. (2017b), Asaduzzaman et al. (2019), Azizunnesa et al. (2010), Bag et al. (2010), Bhuiyan et al. (2008), Das et al. (2018), Habib et al. (2003), Habib et al. (2008), Habib et al. (2009), Habib et al. (2010b), Hamid et al. (2017), Hasanuzzaman et al. (2012), Hossain et al. (2018), Huque et al. (2010), Kamal (2010), Karim et al. (2019), Khan et al. (2000), Khan et al. (2010), Khan et al. (2012), Mostari et al. (2007), Nahar et al. (2016), Nath et al. (2016), Rabeya et al. (2009), Rahman et al. (2016), and Sarker et al. (2015).

TABLE 6 | Milk production of Red Chittagong cattle and its composition.

Parameters	Average	*SD*	*N*	Minimum	Maximum	Total cattle observation
Lactation length, days	228	24	23	161	265	2,805
Lactation milk production, L	618	124	21	453	838	1,579
Milk composition, % fresh milk						
Lactose	5.6	0.21	6	5.3	5.8	119
Milk protein	3.8	0.25	12	3.2	4.1	199
Milk fat	4.8	0.39	13	4.2	5.3	211
Solids not fat (SNF)	9.4	0.94	13	10.8	8.1	211
Total solids	14	1.24	13	13	16	211
Ash	0.3	0.32	3	0.2	0.7	46

SD, standard deviation; N, number of articles that reported the parameters. From Alam et al. (2007), Asaduzzaman et al. (2017a), Asaduzzaman et al. (2017b), Azizunnesa et al. (2010), Bag et al. (2010), Bhuiyan et al. (2008), Debnath et al. (2003), Ferdous et al. (2019), Habib et al. (2003), Habib et al. (2009), Habib et al. (2010a), Hasanuzzaman et al. (2012), Hossain et al. (2018), Huque et al. (2010), Islam et al. (2015), Khan and Mostari (2015), Khan et al. (2000), Khan et al. (2010), Khan et al. (2012), Mostari et al. (2007), Nath et al. (2016), Rahman et al. (2016), Reza et al. (2008), Sarker et al. (2015), and Sarker et al. (2019).

analysis. It also possesses moderate heritability of its productive traits, ranging from 0.38 to 0.49 (**Table 2**; Alam et al., 2007; Rabeya et al., 2009; Afroz et al., 2011, 2012; Rahman et al., 2016; Ferdous et al., 2019). The moderate heritability of traits imply that additive gene action may play a role in regulating them, and their improvement may be possible by improved management and selection practices. Bhuiyan et al. (2007b) also reported selective breeding programs as a key tool for the development of RCC.

PHENOTYPE

The phenotypic traits of RCC shown (**Figure 2**) are taken from Bag et al. (2010) and Bhuiyan et al. (2008) and are presented in **Table 3**. The measurements of mature male and female Red Chittagong cattle body parts are provided in **Table 4** and were taken from Bag et al. (2010) and Habib et al. (2003). The RCC is a readily distinguishable reddish indigenous cattle genotype with greater average body length, height at wither and heart girth (111–132, 107–125, and 123–147 cm, respectively; **Table 5**) than non-descriptive indigenous and North Bengal gray cattle (106, 100, and 129 and 100–105, 93–94, and 122–127 cm, respectively; Hamid et al., 2017), but much lower than Pabna cattle (164, 118, and 148 cm, respectively; Hamid et al., 2017). Therefore, RCC may be regarded as a medium-size breed amongst native Bangladeshi genotype, but a small genotype compared to crossbreds or temperate breeds.

TABLE 7 | Prevalence of diseases and parasites in Red Chittagong cattle.

Prevalence of diseases and parasites (% cattle)	Cattle genotypes			Total cattle observation
	Red Chittagong cattle	Local	Crossbreds	
Gastrointestinal parasites	55	64	71	100
Blood parasites	9	-	13	560
Subclinical mastitis	28	31	56	198

From Ahmed et al. (2015), Chowdhury et al. (2017), Quaderi et al. (2013), and Siddiki et al. (2010).

GENOTYPE ENVIRONMENT INTERACTION

Production and Reproduction

The productive and reproductive characteristics of the RCC breed are provided in **Table 5**. Overall, the birth weight of the RCC calf was between 14 and 16 kg (**Table 5**) similar to non-descriptive indigenous, but lower than Pabna, and North Bengal gray cattle (15, 21, and 18 kg, respectively; Bhuiyan, 2013). RCC heifers reached puberty 5, 9, and 7 months earlier than Munshiganj, Pabna, and Sahiwal cattle genotype in Bangladesh (34, 38, and 36 months, respectively; Bhuiyan, 2013). The gestation period of RCC (283 ± 3 days) was similar to other cattle genotypes in Bangladesh and the post-partum estrus of the RCC cow (96 ± 33 days) was lower than Sahiwal and Sindhi crossbreeds (105 and 127 days, respectively; Islam et al., 2014a). The mature live weight of RCC (180–342 kg) was greater than indigenous cattle (120–180 kg; BLRI, 2004), but lower than crossbreds (300–550 kg; BLRI, 2004).

The calving interval of RCC at 14 months (14 months; **Table 5**) was similar to non-descriptive indigenous cattle, North Bengal gray, and Pabna cattle (15, 15, and 14 months, respectively; Bhuiyan, 2013). The service per conception (1.5; **Table 5**) was greater than non-descriptive indigenous, Pabna cattle, North Bengal gray, and Munshiganj cattle of Bangladesh (1.4, 1.3, 1.4, and 1.3, respectively; Bhuiyan, 2013) and calf survivability was 94% which was similar to non-descriptive indigenous, but higher than crossbreds at farm level (83%; Khan et al., 2012). The RCC cow reached puberty at 29 months, gave birth every 14 months and returned to heat by 96 days post-partum, better than other indigenous and crossbred cattle in Bangladesh.

The quantity and quality of RCC milk is presented in **Table 6**. On average, the RCC cow produced 618 L of milk across a 228-day lactation period, with a daily milk yield of 2.7 L/day, which contained high fat and protein content. The greatest RCC milk production herd was from the Bangladesh Livestock Research Institute (BLRI) recorded to be 838 L from a 219-day lactation (4 L/day; Khan and Mostari, 2015). In the BLRI herd, 18% of the cows produce more than 1,000 L of milk in a lactation, with the greatest recorded production from a single cow being 1,436 L in one lactation (Khan and Mostari, 2015). This high phenotypic variation in milk production per lactation (618–1,436 L) suggests that there is a great prospect for the development of RCC through selective breeding. Production of 1,436 L milk per lactation is substantial from a mature RCC cow of 180 kg live weight (**Table 5**), and it would be equivalent to ∼6,000 L/lactation from a modern Holstein Friesian of 700 kg mature live weight. This suggests that the feed conversion ratio of RCC could be similar to Holstein Friesian cows but there is no comparative study available on this issue. A 2-year comparative study at farm level reported greater lactation length and milk yield of RCC (265 days and 597 L, respectively) than non-descriptive indigenous varieties (258 days and 497 L, respectively), but lower than crossbreds (285 days and 1,272 L, respectively) (Khan et al., 2012). However, rearing RCC was reported to be more profitable than Holstein x local crossbred cows based on lifetime production performance (Khan et al., 2012). These researchers reported greater calving rate and calf survivability and lower calving intervals of RCC compared to crossbred cows. In addition, feed requirements, health and reproduction costs of RCC were lower compared to crossbred cows. The fat content of RCC milk (4.8%; **Table 6**) was greater than indigenous and Holstein crossbreds in Bangladesh (3.7 and 3.4%, respectively for indigenous and crossbreds; Islam et al., 2014b). Also, RCC milk contained greater milk protein and lactose (3.8 and 5.6%, respectively; **Table 6**) compared to indigenous cattle (3.6 and 5.1%, respectively), Holstein crossbreds (2.7 and 4.6%, respectively), and buffaloes (3.5 and 4.7%, respectively) (Islam et al., 2014b).

Disease Resistance

The prevalence of diseases and parasites in RCC is presented in **Table 7**. RCC cattle is more resistant to common diseases and parasites than other native and crossbreds. The prevalence of gastrointestinal parasites in RCC was about 9 and 16% lower than local cattle and crossbreds, respectively (Ahmed et al., 2015; Chowdhury et al., 2017). Blood parasites were also 4% less prevalent in RCC than crossbreds (Siddiki et al., 2010). Subclinical mastitis in RCC was half the prevalence in crossbreds (Quaderi et al., 2013).

CONCLUSIONS AND RECOMMENDATIONS

Red Chittagong cattle are a red colored, small-sized genotype that are more fertile and resistant to common parasites and diseases compared to crossbreds and suitable for the small-holder farmers in the tropics. This genotype has the potential to be developed as a native dairy cattle breed of Bangladesh by the establishment of a well-planned, long-term, selective breeding program due to the high genetic and phenotypic variation within the current population. Also, promoting the benefits of this genotype across Bangladesh may help conserve this genetic resource at a farm level. A long-term plan is necessary to benchmark its current distribution throughout Bangladesh and its impact on smallholder farming. In addition, research is required as to the mechanisms enabling their resistance to environmental stress and tropical diseases.

AUTHOR CONTRIBUTIONS

ND literature search, data synthesis, imagery processing, and drafting manuscript. CC and MI conceptualizing, literature search, drafting reviewing, and editing of manuscripts. CC, MI, NS, and MJ supervising the work. All authors contributed to the article and approved the submitted version.

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Individual Monitoring of Behavior to Enhance Productivity and Welfare of Animals in Small-Scale Intensive Cattle Grazing Systems

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To enhance productivity and welfare of individual animals maintained as a group, management based on individual behavioral tendencies is essential, which requires individual monitoring of animal behavior. Several behavior monitoring systems are currently available to livestock producers. The data obtained from these systems are analyzed to detect significantly high or low frequencies or intensities of behavior associated with estrus, calving and poor health conditions based on thresholds or past trends of the monitored individual. However, because behavior under grazing is more complex and changeable than under confinement, behavioral symptoms are more difficult to detect, and on-farm monitoring of individual animal behavior has been less validated and utilized in grazing systems. Nevertheless, individual monitoring of all animals in a herd is more feasible and cost-effective in small-scale intensive grazing systems because these systems pursue high productivity at the individual level with smaller herd size than large-scale extensive systems. Individually tailored management to enhance productivity and welfare will be possible by focusing on inter-individual differences in behavior within a herd. Behavior of an individual can be analyzed and understood in more detail by comparing it with those of the herd mates. Higher or lower levels of specific activities than the other animals can be associated with health disorders, temporal changes in physiological states, or productivity- or welfare-related traits. More sensitive monitoring and detection of behavioral responses of individuals to changes in nutritional, physical and social environments will lead to more efficient and welfare-conscious management that better meets the needs of individuals.

Keywords: accelerometer, behavioral consistency, cattle, GPS, individually tailored management

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IMPORTANCE OF INDIVIDUAL MONITORING OF ANIMAL BEHAVIOR

Behavior of animals maintained as a group such as cattle has often been represented as an average of the herd, and the average has been used to aid management as an indicator of external and/or internal environments of animals. In grazing systems, for example, decreased daily grazing time under extended stocking in a paddock, as a possible indicator of depleting forage availability, can be used to assess the need for supplementary feeding or switching to a new paddock. Prolonged resting time during the summer days, as an indicator of heat stress, can be a consideration for modification of the access time to pasture. However, individual animals exhibit different behavioral tendencies due to differences in traits such as age, sex, body size, physiological and emotional states, social dominance, past experiences and personality. Hence, management based on the average behavior does not equally benefit all animals in the herd and may even negatively affect animals biased from the average (Richter and Hintze, 2019). To enhance productivity and welfare of individual animals, individually tailored management based on individual behavioral tendencies is essential, which in turn requires individual monitoring of animal behavior. Technological advances and cost reductions in sensor use are making it feasible to constantly and precisely monitor behavior of individual animals in a herd with minimal interference. In this mini-review, we aimed at (1) briefly reviewing current situation of commercially available monitoring systems of animal behavior and (2) assessing prospects and challenges for individual monitoring of behavior to enhance productivity and welfare of animals, with particular reference to small-scale intensive cattle grazing systems. Here, "small-scale intensive grazing systems" refer to the systems in which fenced sward paddocks are rotationally or seasonally grazed by some hundreds of animals or less according to forage availability, while pursuing high productivity at the individual level, as distinct from pastoralism systems on rangelands covering the landscape.

CURRENT SITUATION OF COMMERCIALLY AVAILABLE MONITORING SYSTEMS OF ANIMAL BEHAVIOR

Several monitoring systems of individual animal behavior are currently available to livestock producers. These systems generally include wearable devices to mount on animals, terminals to remotely collect data from the devices and applications to see and manage behavioral data on smart devices. In cattle production systems, devices including three-axis accelerometers (with additional sensors) to mount on the neck [e.g., Farmnote® (Farmnote Holdings Inc., 2020) and U-motion® (Desamis Co. Ltd., 2020)], an ear [CowManager® (CowManager, 2020)] or a hind leg [CowAleart® (IceRobotics Ltd., 2020)] of an animal are currently most popular because data on static and dynamic acceleration can respectively provide information on angles and movements to classify the posture and behavior of the animal (Andriamandroso et al., 2017). Information on daily activity patterns (time spent feeding, ruminating, resting, drinking, etc.) and activity intensities or step counts can be obtained from these systems. The time-series behavioral data are analyzed to detect significantly high or low frequencies or intensities of behavioral variables associated with estrus (Valenza et al., 2012), calving (Saint-Dizier and Chastant-Maillard, 2015) and poor health conditions such as lameness (Thorup et al., 2015) and dysstasia (difficulty in standing) based on thresholds or past trends of the monitored individual. The behavioral information is useful to avoid missing the timing of artificial insemination, to decrease accidents at calving (e.g., fetal death due to dystocia) and to find and treat health disorders in early stages, and thus can reduce economic loss and enhance management efficiency. Despite the recent spread into various systems (cow-calf or fattening of beef, or dairy), on-farm monitoring of individual cattle behavior has been primarily validated and utilized in confinement systems such as free-stall barns, with much fewer uses in grazing systems (Jaeger et al., 2019).

PROSPECTS AND CHALLENGES FOR GRAZING MANAGEMENT BASED ON INDIVIDUAL ANIMAL BEHAVIOR

Behavior under grazing is more complex and changeable than that under confinement because animals adapt their behavior to their ever-changing environments such as sward and weather conditions. Therefore, behavioral symptoms are more difficult to detect under grazing (Kamphuis et al., 2012). Nevertheless, individual monitoring of all animals in a herd is more feasible and cost-effective in small-scale intensive grazing systems because these systems pursue high productivity at the individual level with smaller herd size than large-scale extensive systems. Data transfer from animal-mounted devices to a terminal is also easier in small-scale systems because animals visit a fixed place such as a barn every day. Information on continuous individual animal behavior around the clock can be much more detailed than a single manual inspection per day, and to some extent, but not completely, it can replace manual labor to monitor animals, thus saving time and money (Herlin et al., 2021). In addition, although daily visual observations or milk yield and quality information can help managers to notice clear abnormalities or clinical signs such as lameness or mastitis, behavioral monitoring has a potential to capture minor changes in individuals and early signs of abnormality. The current financial constraints on the introduction of the systems will be acceleratingly reduced through a cycle of further increasing production and decreasing prices along with the widespread use. In the near future, the monitoring systems of behavior are expected to be adopted widely in small-scale intensive grazing systems, and producers will be able to know daily behavior of all of their animals. What findings and benefits for enhancement of productivity and welfare of animals can be gained from individual monitoring of behavior in small-scale intensive grazing systems?

Even though behavior under grazing is complex and changeable, individually tailored management to enhance productivity and welfare will be possible by focusing on inter-individual differences in behavior within a herd. Behavior of an individual within a herd can be analyzed and understood in more detail by comparing the time-series data of the individual with those of the herd mates. Through the improved detection algorithms, a behavioral change in an individual can be judged as a change deviated from the herd mates (**Figure 1A**) or synchronized with them (**Figure 1B**). Even if an individual

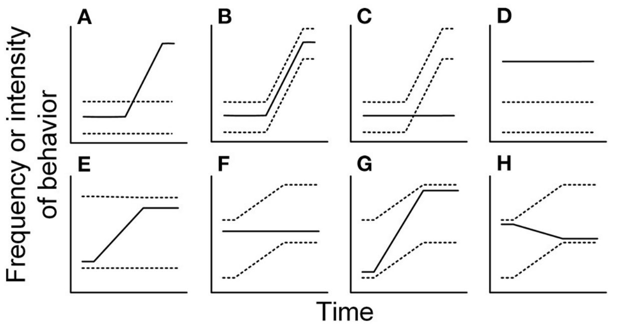

FIGURE 1 | Schematic diagrams of comparison of time-series behavioral data between an animal (solid lines) and the herd mates (dotted lines). By comparing individual behavior with those of the herd mates, a behavioral change in an individual can be judged as a change deviated from the herd mates **(A)** or synchronized with them **(B)**. Even if an individual maintains behavioral stability, the animal can be detected as an outlier when a difference from the herd mates is generated **(C)** or maintained **(D)**. The comparison can also detect an animal that behaves differently from the herd mates but not as distinctly as an outlier **(E–H)**.

maintains behavioral stability, the animal can be detected as an outlier when a difference from the herd mates is generated (**Figure 1C**) or maintained (**Figure 1D**). The comparison can also detect an animal that behaves differently from the herd mates but not as distinctly as an outlier (e.g. **Figures 1E–H**). Higher or lower levels of specific activities in an animal than the others can be associated with health disorders, temporal changes in physiological states or higher or lower behavioral responsiveness to the environment (behavioral plasticity; Biro and Adriaenssens, 2013). Longer time spent grazing by an animal than the herd mates may be suspected as a temporal negative energy balance (Matthews et al., 2012). Although such cases are often seen in cows in early lactation stages, such animals may lose their body weights and conditions, which results in reproductive inefficiency and temporary deprivation of freedom from hunger, one of the Five Freedoms (Farm Animal Welfare Council, 1993). Temporary isolation of such animals from the herd and intensive treatment may mitigate the negative energy balance. Individually tailored supplemental feeding according to each animal behavior is also effective if feeders that can identify individuals are available. However, efficient management methods for individual animals kept mainly on pasture need to be developed in the future. Health alarms based on the outlier detection of a few behavioral indicators may lead to a high number of false positive alerts, as with the detection models based on thresholds (Brassel et al., 2019). Data collected from various automatic recording technologies need to be processed and integrated into a single outcome of animal production or welfare (which is easy to understand by the consumer) (Stygar et al., 2021). Further research is required to develop methods to effectively combine multiple behavioral indicators with each other and with physiological indicators obtained from milking robots and other sources and to integrate different analytical algorithms (threshold-based detection and comparison within a herd).

Consistently higher or lower tendency of behavioral variable values over a long period (e.g., years) can be related with less changeable individual traits such as personality (**Figure 1D**). Owing to increasing interests in animal personality and similar concepts such as temperament, behavioral syndrome and coping style, the relationships of behavioral consistency with fitness (Smith and Blumstein, 2008) and energy metabolism (Biro and Stamps, 2010), which support growth, survival and breeding success of individuals, have been investigated and discussed for various species of animals. Cattle personality has been found to be associated with productivity-related traits [e.g., weight gain (Petherick et al., 2009), feed conversion efficiency (Gregorini et al., 2015), days from calving to body weight nadir, calf weaning weight (Wesley et al., 2012), carcass quality (Hall et al., 2011), and milk and fat yield (Jaeger et al., 2019)] and welfare-related traits [e.g., body condition score as a measure of hunger (Matthews et al., 2012) and somatic cell count as a measure of udder health (Jaeger et al., 2019)]. Since several personality traits are heritable (García et al., 2020), application of the associations to breeding programs of a herd by selecting animals that have more productive and adaptive personality traits may enhance productivity and welfare of animals. However, this idea is still controversial because the risks along with reduced variation of behavioral traits are still unknown (Richter and Hintze, 2019). Because past experience affects individual behavioral traits, giving opportunities to gain desirable behavioral traits during development can enhance lifetime productivity (Mulliniks et al., 2016) and welfare (Richter and Hintze, 2019) of animals. Further research is warranted for the relationships of personality with productivity- and welfare-related traits of individual animals.

Incorporation of GPS into the monitoring systems can provide valuable information on movement and spatial distribution of individual animals under grazing (Bailey et al., 2018). Traveling distance can be used as a proxy of energy expenditure (Brosh et al., 2006). Spatial distribution can be related with exploration–avoidance dimensions of livestock temperaments (Wesley et al., 2012). Inter-individual positional relations such as distance from herd mates and spatial position relative to herd movement that can be calculated from GPS data can provide information on sociability, leadership and dominance of individuals (Šárová et al., 2010).

More sensitive monitoring and detection of behavioral responses of individuals to changes in nutritional, physical and social environments will lead to more efficient and welfare-conscious management that better meets the needs of individuals in small-scale intensive grazing systems.

AUTHOR CONTRIBUTIONS

HA conceived the idea and prepared the review. MH contributed to the content, wrote parts, and edited the manuscript. Both authors contributed to the article and approved the submitted version.

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