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Agroecology in policy and practice

Edited by
Rachel Bezner Kerr, Hans Rudolf Herren, Barbara Gemmill-Herren,
Caterina Batello Cattaneo and Franz-Theo Gottwald

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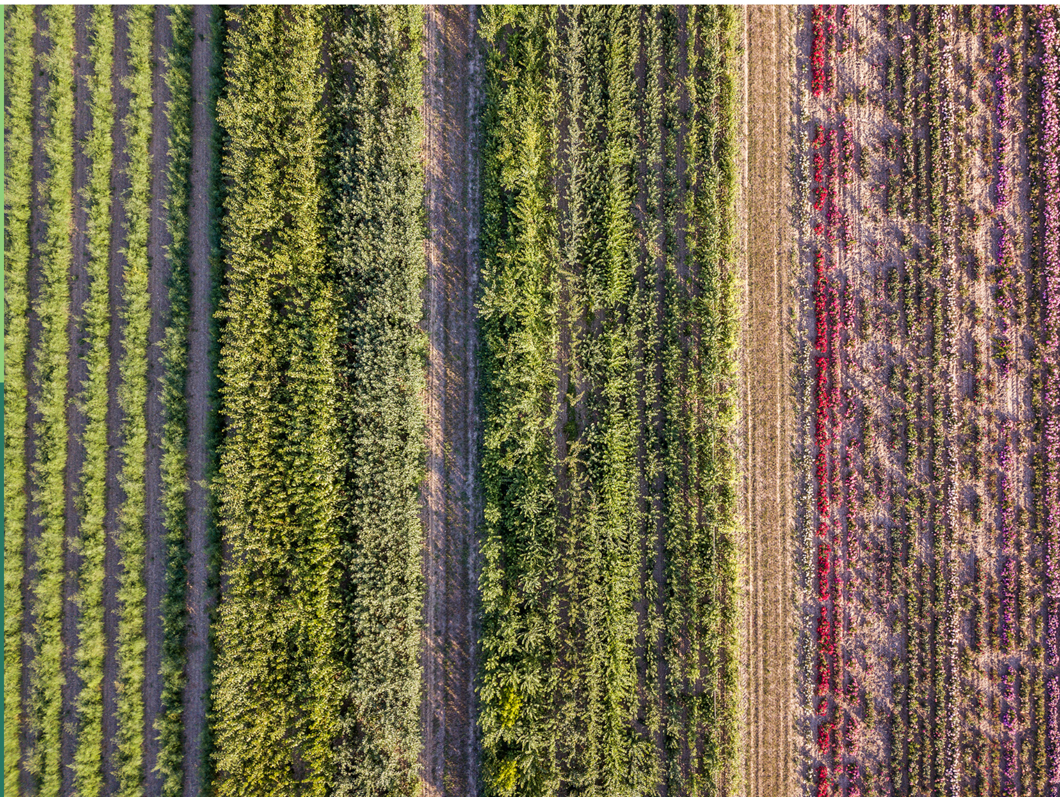

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Agroecology in policy and practice

Topic editors
Rachel Bezner Kerr — Cornell University, United States
Hans Rudolf Herren — Independent researcher, United States
Barbara Gemmill-Herren — Prescott College, United States
Caterina Batello Cattaneo — Food and Agriculture Organization of the United Nations (Italy), Italy
Franz-Theo Gottwald — Humboldt University of Berlin, Germany

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EDITED AND REVIEWED BY
Stacy Michelle Philpott,
University of California, Santa Cruz,
United States

*CORRESPONDENCE
Barbara Gemmill-Herren
bg11@mac.com

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Editorial: Agroecology in policy and practice

Barbara Gemmill-Herren[1]*, Franz-Theo Gottwald[2], Caterina Batello[3], Rachel Bezner Kerr[4] and Hans R. Herren[5]

[1]Prescott College, Prescott, AZ, United States, [2]Faculty of Life Sciences, Albrecht Daniel Thaer Institute for Agricultural and Horticultural Sciences, Humboldt University of Berlin, Berlin, Germany, [3]Agroecology Europe - A European Association for Agroecology, Paris, France, [4]Global Development, College of Agriculture and Life Sciences, Cornell University, Ithaca, NY, United States, [5]Millennium Institute, Washington, DC, United States

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Editorial on the Research Topic
Agroecology in policy and practice

In the past years, there has been steady growth in research and work relating to agroecology. People-centered, knowledge-intensive, and rooted to sustainability, it is now well-established that agroecology's holistic approach matches the transformation to food systems called for by the 2030 Agenda; a transition to sustainable food and agriculture systems that ensures food security and nutrition for all, provides social and economic equity, and conserves biodiversity and the ecosystem services on which agriculture depends. Although not a new concept, agroecology is gaining interest worldwide among a wide range of actors as an effective answer to climate change and the interrelated challenges facing food systems, finding expression in the practices of food producers, in grassroots social processes for sustainability and in the public policies of many countries around the world.

While agroecological elements have been applied and honored by communities for centuries, they have rarely received much respect in the intergovernmental and scientific communities until fairly recently. Regional networks such as SOCLA in Latin America, Alliance for Food Sovereignty in Africa and the Asian Farmers Association for Sustainable Rural Development in Southeast Asia increased interest, practice, and support for agroecology. At the international level, the process for a food system transformation started with the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD)- a UN initiated process calling for agroecology. Two international symposia convened by the Food and Agriculture Organization of the United Nations, multiple regional symposia, the adoption of the Ten Elements by FAO's governing body, and the commissioning of the High Level Panel of Experts report to the World Commission on Food Security on "Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition" among other initiatives further demonstrate that Agroecology has landed on the global agenda.

In recognition of this, the World Futures Council 2018 Future Policy Award was dedicated to recognizing policies that scale up agroecology, contribute to the protection of life and livelihoods of small-scale food producers, ensure sustainable food production systems, and implement climate resilient agricultural practices. As a follow up, WFC facilitated this special issue of Frontiers in Sustainable Food Systems on "*Agroecology in Practice and Policy.*" The aim of this Research Topic was to gather contributions from scientists and practitioners working in diverse disciplines who have common interests in agroecology policy and practice. We asked for examples contributing to the protection of the life and livelihoods of small-scale food producers and empowering them, nurturing sustainable food production systems, promoting resilient agricultural practices that help maintain ecosystems, strengthening capacity for adaptation to climate change, and progressively improve land and soil quality. An overarching goal was to demonstrate the breadth of agroecology policy and practice, and foster understanding between different scientific communities who may not always be aware of one another's work. We looked for contributions about policy and practice examples that would inform about the opportunities and challenges of agroecology as well as entail a set of recommendations for a range of stakeholders (policymakers, academia, NGOs, international organizations, etc.) on what has to be done, in order to scale up agroecology in that particular context. Furthermore, we were interested in methodologies to identify and evaluate agroecology policy and/or practice examples.

Under the umbrella of this Research Topic, a total of 13 articles were published. We were open to a wide variety of types of articles. Amongst them were mostly Original Research (6), but also articles on Methods (1), Hypothesis and Theory (2), Policy & Practice Reviews (1), Reviews (2), and Systematic Review (1). We elaborate on the different types of articles publish and provide more detailed description of a few of them below.

A good number of articles examined public policies and their impact, such as the one on *Brazil's semi-arid region* (Brandão et al.) or those on the *Ecuadorian capital Quito* (Rodríguez et al.) and *Los Angeles in the US* (Daniels and Delwiche). Both cities have stepped up their work for agroecological urban agriculture and food resilience and their policies in this regard were honored with the Future Policy Award 2018 of the World Future Council, FAO, and IFOAM-Organics International. Struggles at different levels shape these public policies, from local arenas to national and the international food policy arena. As the article on "*the innovation imperative*" well-exemplifies, often disputes occur at the level of discourse (Anderson and Maughan). As can be anticipated by the advancement of a system of food and farming that challenges the conventional model of high-input production—even if this is showing many weaknesses, Agroecology has met with considerable forces to push back and reshape its key concepts. As articulated in the article by Anderson and Maughan, as the transformative concept of Agroecology has entered mainstream discursive arenas such as intergovernmental fora, it has been subjected to an "innovation frame," which poses a number of issues not just for Agroecology, but for sustainability transformations in general. This insightful article- analyzing the discourse around public comments—is very helpful in parsing the complex dialogue around an ultimately political and social—as well as agronomic-topic.

Another set of articles researched agroecology practices, their benefits and challenges to implementation, such as the significance of *long-term nutrient management in an intensive rice-wheat cropping system for soil sulfur* (Meena et al.). Articles are available on *the complexity of smallholders' intense use of glyphosate in maize crops from South Mexico* (Monroy-Sais et al.) or on benefits of *decentralized wastewater treatment for rural villages in India* (Friedrichsen et al.). One of these takes a particular farming system as a point of departure: Freed et al. focus on the *importance of maintaining diversity of integrated rice and fish production*, a production system in Asia with tremendous scope for holistic approaches.

A focus on strong local food systems, conferring diversity and circular economies on communities, is central to agroecological approaches. The article by Heindorf et al. illustrates the substantial contribution of local food markets to maintaining agrobiodiversity in region of Huasteca Potosina, Mexico. Yet the skewed proportion of markets fostering such biodiversity points to the need for political action to maintain and promote this diversity into the future.

Last but not least, a third set of articles are dedicated to research methods for evaluating agroecology. One of the expected responses to a system that challenges the status quo is to ask for more evidence of its performance. Evidence of agroecological approaches has been well-documented in its many beneficial aspects, including environment, food and nutrition security, and households' incomes, all the more remarkable in the face of the reality that research into agroecology has been consistently underfunded (Biovision Foundation for Ecological Development and International Panel of Experts on Sustainable Food Systems, 2020). Nonetheless, performance evaluation has been one of the requests on the intergovernmental level, in particular from the 26th Committee on Agriculture of the United Nations Food and Agriculture Organization (COAG, 2018). Recognizing that this request provides an opportunity to compile global, multi-scalar, and multi-dimensional documentation in a format that can be used to inform policy-making processes, 70 representatives of agroecology-related organizations worldwide worked together to respond to this need. The article by Mottet et al. in this special issue documents the process undertaken to develop such a tool, called "TAPE: Tool for Agroecology Performance Evaluation." One can only hope that initiatives to develop such metrics- such as the newly-launched CGIAR Program on Agroecological Transitions Program for Building Resilient and Inclusive Agricultural & Food Systems -will build on this well-elaborated foundation (CGIAR, 2023).

The research focused articles in this special issue argue for *a new understanding of the centrality of agroecosystem actors and their capacity for agency* (Gallardo-López et al.), and for *the need of long-term participatory action research (PAR) in agroecology* (Sachet et al.). One can find practical recommendations, which requires addressing specific questions in research, technology, and policy development. The article by Tittonell et al. on *how to mainstream agroecology among large scale farmers* makes the point that large scale conventional/industrial farming uses 70% of the agricultural land area, and therefore cannot be ignored as a huge potential for transformation toward agroecological practices. Given the amount of subsidies that this sector received, it presents an opportunity to redirect these subsidies toward the transformation and achieve many objectives that relate to the conservation and promotion of biodiversity, with nature inclusive agricultural landscapes that re-establish ecosystem services, and manage water and nutrient cycles. Such an agroecological redesign requires a change in policies along the entire value chain, backed by a new research agenda that will address the farmers needs for the deep system transformation.

In sum, this special issue provides in-depth analysis of a range of policies, practices and research methods which support agroecology in many regions around the world, further opening the space for agroecology. Looking forward to more research on this topic, we are thankful to all contributors and especially toward Frontiers, guiding us through the rigorous scientific peer-review selection process.

Author contributions

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

Conflict of interest

CB was employed by Food and Agriculture Organization of the United Nations (Italy). HH was employed by Millennium Institute.

The remaining authors declare 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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References

Biovision Foundation for Ecological Development., and International Panel of Experts on Sustainable Food Systems (2020). *Money Flows: What Is Holding Back Investment in Agroecological Research for Africa?* Biovision Foundation for Ecological Development & International Panel of Experts on Sustainable Food Systems. Available online at: http://www.ipes-food.org/pages/MoneyFlows

CGIAR (2023). *Program on Agroecological Transitions Program for Building Resilient and Inclusive Agricultural and Food Systems*. Available online at: https://glfx.globallandscapesforum.org/topics/21467/page/agroecological-transitions

COAG (2018). *Agroecology: From Advocacy to Action*. Twenty-Sixth Session. Rome: Committee on Agriculture.

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Family Farmers' Perceptions of the Impact of Public Policies on the Food System: Findings From Brazil's Semi-Arid Region

Emily Aparecida Ferreira Brandão [1], Thiago da Rocha Santos [2] and Stephan Rist [3]*

[1] Faculty of Science and Natural Sciences, Institute of Geography, University of Bern, Bern, Switzerland, [2] Cooperativa Sertão Forte de Casa Nova e Região (COOAF), Casa Nova, Bahia, Brazil, [3] Centre for Development and Environment (CDE) and UNESCO Chair on Cultural and Natural Heritage and Sustainable Mountain Development, University of Bern, Bern, Switzerland

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Edited by:
Hans Rudolf Herren,
Independent researcher, United States

Reviewed by:
Gabriel da Silva Medina,
University of Brasilia, Brazil
Imme Scholz,
Deutsches Institut für Entwicklungspolitik (DIE), Germany

***Correspondence:**
Emily Aparecida Ferreira Brandão
emilyfbrandao@gmail.com

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The global narrative on food sustainability revolves around the need to improve food security, right to food, environmental performance, social-ecological resilience, reducing poverty, and inequality. Such principles were guiding a food policy shift for addressing the needs of family farmers, taking place in Brazil. However, how these policies were seen from the point of view of family farmers has not yet been investigated sufficiently. Consequently, this paper presents the results of an assessment of how food policies have impacted the food system in terms of production practices, market structure, land access, and food security, through the perception of family farmers. Our study concerns the semi-arid part of the state of Bahia (Brazil), in which rainfed food systems prevail. The perception of family farmers on the food policies related to credit, public procurement, technology, knowledge, and land access showed three main results: (1) concerning production practices, there was an increase in crop diversification (formerly collected wild plants are currently cultivated) and the dissemination of agro-ecological techniques (organic matter as a fertilizer and seed bank). However, credit is limited, not being translated into significant investments in the production process; (2) with regard to market structure, the public food procurement programs created a specific market for farmers assuring to provide reliable and stable income and trade through economies of scale. The negative factor regarding public food procurement programs is the dependence of farmers from institutional markets organized by the government; (3) food security was increased, due to the stable income, but the lack of policies directed at on-farm autonomy makes production for self-consumption difficult to be achieved. Also, the legal basis for land access does not meet the expectations and needs of farmers, placing them in a position of vulnerability to land grabbing. We conclude that the new food public policies had positive impacts, through a double strategy, consisting in first, the improvement of individual food system activities, and second, interconnecting single food system activities in such a way that they create synergies among them, in view of basic principles of sustainable food systems.

Keywords: food system, public policies, Fundo de Pasto communities, actors's perception, food sustainability

INTRODUCTION

The productivist paradigm emerged 60 years ago as a seemingly straightforward approach to tackling food insecurity by increasing food production (de Schutter, 2014). The so-called Green Revolution—based on mechanization and intensive use of agro-industrial inputs, natural resources, and chemical fertilizers—served as the main policy strategy for boosting agricultural productivity and solving the mismatch between supply and demand for food (Borlaug and Dowswell, 2003). After decades of such policy, however, a 2006 Food and Agriculture Organization report showed that, despite per capita increases in agricultural output, the percentage of hungry people only slightly declined from 1950 to the 1990s (FAO, 2006). And more recent data from 2018 showed that while more than enough food was produced to feed the global population in a year, as much as 34% of it never even reached the tables of consumers, leading to 821 million people being food insecure (FAO, 2019b). Indeed, achieving universal food security requires more complex mechanisms that consider political interventions, sustainability, holistic perspectives, and structural human development (FAO, 2019a).

In 1972, the Stockholm Conference and the Club of Rome unambiguously emphasized the importance of more socially and environmentally friendly development models. The Stockholm Conference was convened by the UN to define sustainable forms of development, and the Club of Rome authored the ground-breaking report "The Limits to Growth," which for the first time denounced humanity's plunder of non-renewable resources, concluding that we will have reached our natural limit of development by the year 2072 if unsustainable models of progress continue (Paul, 1993). Indeed, already decades ago, productivist agriculture and similar approaches caused crises that led to wider environmental and social movements around the world, beginning especially in the mid-1970s. In Brazil, the environmental movement was eventually further strengthened by ongoing struggles for restoration of democracy after years of military dictatorship (Abramovay, 1992; Paschoal, 1995). In the 1980s, measures toward re-democratization brought about important changes in Brazilian political–institutional and social arenas (Santos, 2011), including agriculture. The 1988 Brazilian Constitution set a milestone for recognition of family farming as a professional category, in particular by including family farmers in the country's social security retirement programme (Grisa and Schneider, 2015). Overall, ending hunger and protecting family farmers' rights became official public policy during the government of former President Luiz Inácio Lula da Silva (2003–2010), when various food policies were institutionalized at the federal level.

Against this background, there are many studies—mainly based on regional statistics and modeling—that highlight the socio-economic effects of Brazil's recent food policies on living conditions among the country's family farmers (Sabourin, 2007; Belik, 2010; Silva, 2011; Grisa and Schneider, 2015; Del Grossi, 2019). However, there are few empirical analyses of how farmers perceive the influence of these public policies on food systems at the local level. Thus, the present study aims to fill this research gap by investigating family farmers' perceptions of the socio-economic impacts of Brazil's newer food policies on key food system features, including production practices, market structures, food security, and access to land.

The perceptions of individual actors are an important indicator for use in interpreting social transformation processes and assessing people's subjective motivations and political involvement. Perception is also a relevant construct for evaluating the extent to which a state, in its diverse manifestations, is committed to incorporating historically neglected social groups. Further, social participation and inclusion contribute to proper monitoring of public policies, in addition to being fundamental to representation of collective interests (Soratto and Witt, 2013).

The main research questions that guided this study were: (1) What are farmers' perceptions of impacts of new public policies on different socio-economic outcomes, including production practices, market structures, food security, and access to land? (2) How are these policies and outcomes related to specific features of the food system of family farmers?

CONCEPTUAL FRAMEWORK

The food system approach contributes to understanding the complexities of agricultural activities (input provision, producing food, processing, distributing, and consuming) and key actors by interconnecting inputs, flows, and outputs (FAO, 2018). The food system concept is ideally suited to address the links of food insecurity within wider socio-economic contexts, in contrast to narrowly defined productivist approaches that lead to limited technical solutions. It enables policymakers to view the agricultural system more fully, facilitating policy coordination and diverse actors' participation in building more efficient instruments to tackle food insecurity, poverty, social inequality, environmental degradation, and unsustainable production practices (FAO, 2018).

Rastoin and Ghersi (2010) define a food system as interconnected but independent networks of stakeholders (NGOs, public and private organizations, citizens, financial institutions, and companies) coexisting in a geographic space (region, state, multinational region) that contribute directly or indirectly to generation of flows of goods and services oriented toward meeting the food needs of groups of consumers located in the same geographic space or elsewhere. Some experts define food systems as social-ecological systems (Berkes et al., 2002; Ericksen et al., 2010; Rist and Jacobi, 2016), emphasizing that they are sourced from biophysical and social elements along specific agri-food value chains and, through these, establish human relations around natural resources, information, services, and policy interests.

Public policies play a crucial role in shaping food systems by constructing legal frameworks to achieve food security, supporting investments in family farmers, increasing people's access to markets, and mobilizing societal resources to push food systems toward sustainability—based on resilience, adequate working conditions, environmental integrity, and provision of healthy food (Kay et al., 2018). However, the efficiency of public policies depends on a combination of factors, including the political context, social conventions, people's adaptability to specific production models, and monitoring via popular participation (Perrucci and Perrucci, 2014; Albers et al., 2018).

There is substantial literature debating what would constitute the most appropriate agricultural production practices to achieve sustainable food production (Huang et al., 2002; Phipps and Park, 2002; Tilman et al., 2002; Prasifka et al., 2009). Agricultural production practices range from highly technological models to more ecology-based techniques. Adoption of chemical fertilizers and pesticides and implementation of environmentally taxing production methods generally lead to unsustainable development (Piesse and Thirtle, 2010). However, various other food policies show promise of merging sustainability and productivity aims on behalf of family farmers, including provision of means of production, credit, and fairer conditions of market competition and movement of goods. Historically, production practices such as organic fertilization, seed selection, crop rotation, and biological control of pests have been successfully applied all over the world. More recently, these techniques have been referred to collectively as agroecological practices (Altieri, 1995; Wezel et al., 2009).

Synergies and trade-offs between sustainable agricultural practices and food security cannot be neglected, since food availability and access depend on the conditions under which it is grown, processed, distributed, and consumed (Colonna et al., 2013). Food security is determined by the arrangement and management of food systems, flows of goods, market configurations, diverse actors and their interconnected value-adding activities, and the different scales of production and demand for food that define where and how it is grown, processed, distributed, and consumed (FAO, 2018). The 1996 World Food Summit in Rome defined food security as the situation in which "all people, at all times, have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (FAO, 1996). In the literature, there has been an active debate regarding public procurement of food and school meal programmes as pathways for ensuring food security, since they contribute directly and indirectly to improving food distribution and access (de Schutter, 2010; Sidaner et al., 2013). Public procurement programmes are mediated market models, designed to transform trade into a more "socially efficient" process, guaranteeing basic social welfare needs in rural areas, especially where food-insecure households are prevalent (Rocha, 2007).

Equitable access to land is crucial to achieving food security and sustainable development in countries of the global South, where frequent instances of land grabbing are driven by worldwide demand for food commodities, biofuels, mining and other environmentally taxing and socio-economically demanding goods and activities. The concept of land governance aids understanding of the links between secure land rights and food security (Landesa, 2012). Land governance can be understood as sets of processes comprising access to and use of land and natural resources, the related forms of organization and distribution of political power, and the manner in which conflicting land interests are reconciled (FAO, 2009). The International Land Coalition (ILC, 2010) argues that equitable access to land and sustainable management of natural resources would enable reduction of hunger and poverty while promoting dignified livelihood conditions.

According to the FAO, sustainable food systems are those in which the production, processing, distribution, and consumption of food effectively protect and respect natural resources, biodiversity, and ecosystems, while providing a sustainable diet that is "culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; while optimizing natural and human resources" (FAO, 2010, p. 7). As conceptualized by Rist and Jacobi (2016), food sustainability comprises five pillars: food security, the right to food, reduction of poverty and inequality, environmental integrity, and social-ecological resilience. These can serve as normative foundations to transform the configuration of food systems, going beyond issues of production to incorporate and shape a wide range of aspects related to rural livelihoods.

Figure 1 summarizes how we used the food system approach to build our research questions. It provides a wider perspective on interactions between actors, public policies, and food system activities, the combination of which leads to multiple outcomes.

Our study hypothesis is that food-related public policies implemented to encourage the sustainability and resilience of family farming generate dynamics in the food system that influence value chains and livelihoods, triggering changes in production practices, market structured forms of commercializing family farmers' goods, food security, and land governance. Within the pillars of food sustainability described above (Rist and Jacobi, 2016), we prioritized the pillars of food security and reduction of poverty and inequality in the present research. Some aspects related to environmental sustainability were evaluated as observed impacts in regards to sustainability-related management practices. In the next section, the public policies selected for this study will be detailed, namely.

PUBLIC POLICIES TARGETED AT FAMILY FARMERS IN BRAZIL (STATE OF BAHIA)

Most of the policies were implemented at the federal, regional, and state levels. The majority of the programmes' financial resources were transferred from ministries to states, municipalities, NGOs, and private/public companies tasked with local operationalization of policies. The origin of the funds was centralized, but the policies' implementation, monitoring and operationalization were decentralized. In this section, we will present the main features of the key food policies that were implemented in the study area.

Rural Credit Programmes

The National Programme for Strengthening Family Farming (*Programa Nacional de Fortalecimento da Agricultura Familiar,*

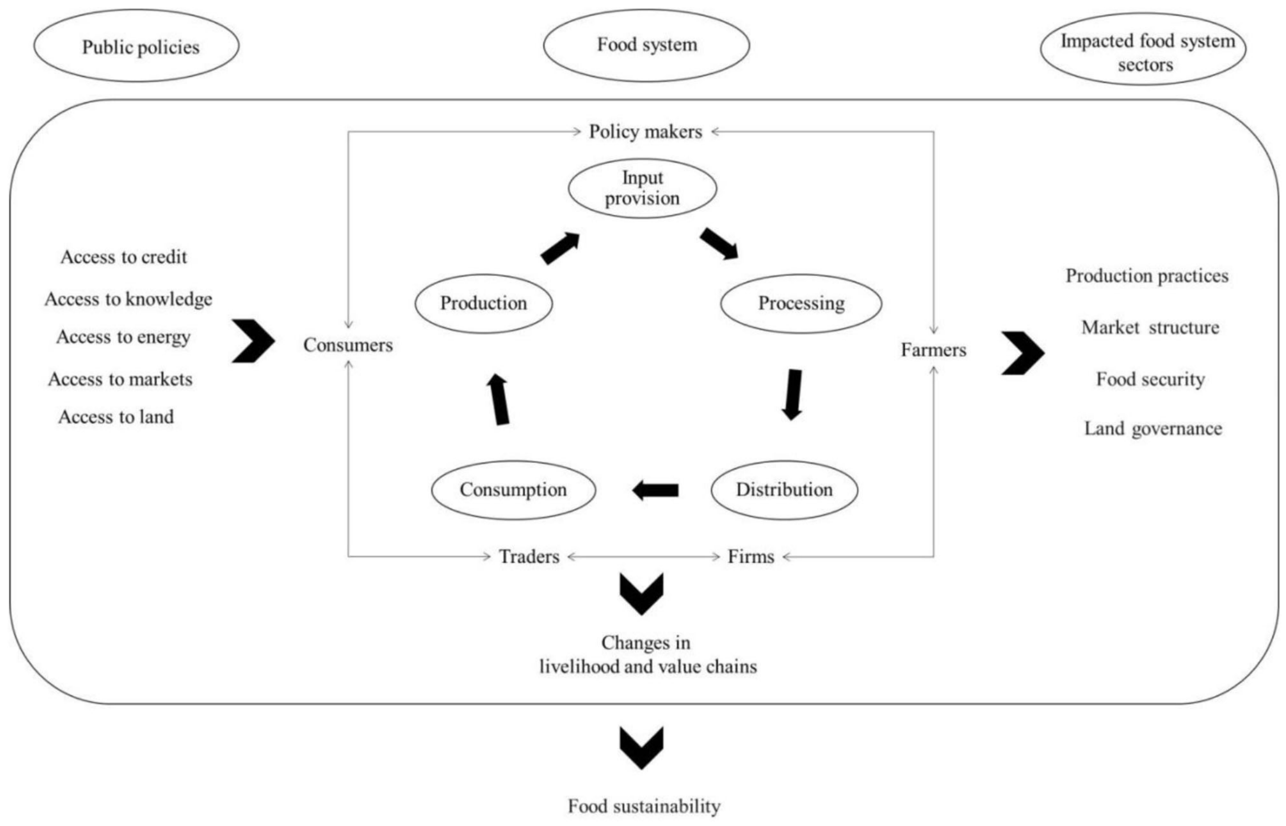

FIGURE 1 | Conceptual framework.

PRONAF) was launched in 1996 and provides credit for productive rural activities, targeted at family farmers (Aquino and Schneider, 2015). The family farmers must be enrolled in a national administrative register such as the Declaration of Aptitude to PRONAF (*Declaração de Aptidão ao PRONAF*, DAP), which is a tool used by Federal Government to identify the Family Units and give them legal recognition. This programme is financially supported by the Ministry of Agrarian Development (*Ministério do Desenvolvimento Agrário,* MDA), and the credit is provided by banks situated around the municipalities.

The *Garantia Safra* was launched in 2002 to grant financial compensation to family farmers who experience weather events (e.g., drought) that damage overall output (MDA, 2019). To become part of the programme, farmers must meet the following criteria: (1) monthly household income of maximum 1.5 times the Brazilian minimum wage; (2) holding between 0.6 and 5 hectares of land; (3) cultivating annual crops (e.g., onions, beans, cassava, maize); and (4) possessing the Declaration of Aptitude to PRONAF (DAP) (SEAD, 2018). The municipality reports to the Ministry of Agrarian Development a loss of 50% of the municipality's crops in the ongoing year. In the following year, the ministry transfers the amount to the municipality, which passes on the money to the family farmers.

Food Security and Mediated Markets

The National School Feeding Programme (*Programa Nacional de Alimentacão Escolar*, PNAE) was first implemented in 1955, and was transformed over the years from a regional focus to a national programme. In 2003, it assumed its current form, with the objective of providing school meals to students in all stages of basic public education. The federal government transfers the financial resources to states and municipalities that must use at least 30% of their total budget to obtain food from the local family farm sector (Brasil, 2009a). To participate in this programme, family farmers must be connected to farmer associations or cooperatives.

The Food Procurement Programme (*Programa de Aquisição de Alimentos*, PAA) was launched in 2003 to provide access to food in sufficient quantity, quality, and regularity for populations in situations of food and nutritional insecurity (Brasil, 2012). The Ministries of Social Development (*Ministério do Desenvolvimento Social*, MDS) and Agrarian Development are responsible for managing and distributing the financial resources to the National Supply Company (*Companhia Nacional de Abastecimento*, CONAB[1]), and state and municipal governments, as these are

[1]CONAB supports the activities carried out by the other entities in the execution of the programme (state and municipal governments). Its main role is to build public food stocks for later transfer to programme beneficiaries CONAB, 2016.

the public bodies operating the programme at the local level. These agencies purchase family farmers' products (individually or via farmer associations or cooperatives) by means of public calls and channel them into public food stocks, which are directed to food insecure communities (Peraci and Bittencourt, 2011; Sambuichi et al., 2019). Further, the food produced and marketed through the PAA is incorporated into the municipal public nutrition programmes of schools, food banks, hospitals, etc. (Sambuichi et al., 2019).

Technology and Knowledge

The programme One Million Cisterns for Drinking Water (*Um Milhão de Cisternas Rurais,* P1MC) was created in 2003 to provide cisterns to family farmers to store rainwater for domestic consumption (MDS, 2017). To benefit from the cistern programme, families must meet the following criteria: (1) live in a rural area; (2) have a per capita income of maximum R$ 154.00 per month (15% of the Brazilian minimum wage); (3) lack access to water; (4) have a house with a roof to capture rainwater; (5) not have been assisted by another programme with the same purpose (Brasil, 2011). The cisterns programme emerged from social mobilizations organized by civil society and the umbrella NGO Semi-arid Articulation (*Articulação Semiárido Brasileiro*, ASA), which operates in the semi-arid region and manages the programme. Though a federal policy, it has a regional focus—the cisterns are mainly distributed in the municipalities of the semi-arid region (MDS, 2017).

Another programme aimed at promoting technology in rural areas is "Light for All" (*Luz para todos*), created in 2003. In isolated rural communities not supplied by electricity-grid networks, the programme provides solar panels. It is a federal policy coordinated by the Ministry of Mines and Energy (*Ministério de Minas e Energia*, MME), operated by the public power company *Centrais Elétricas Brasileiras S. A.* (Eletrobras), and implemented locally by concessionaires (Brasil, 2009b).

Concerning technical knowledge, the Technical Assistance and Rural Extension programme (*Assessoria Técnica e Extensão Rural*, ATER) became policy at the national level in 2010. Its main goal is to transfer technical knowledge to family-farm

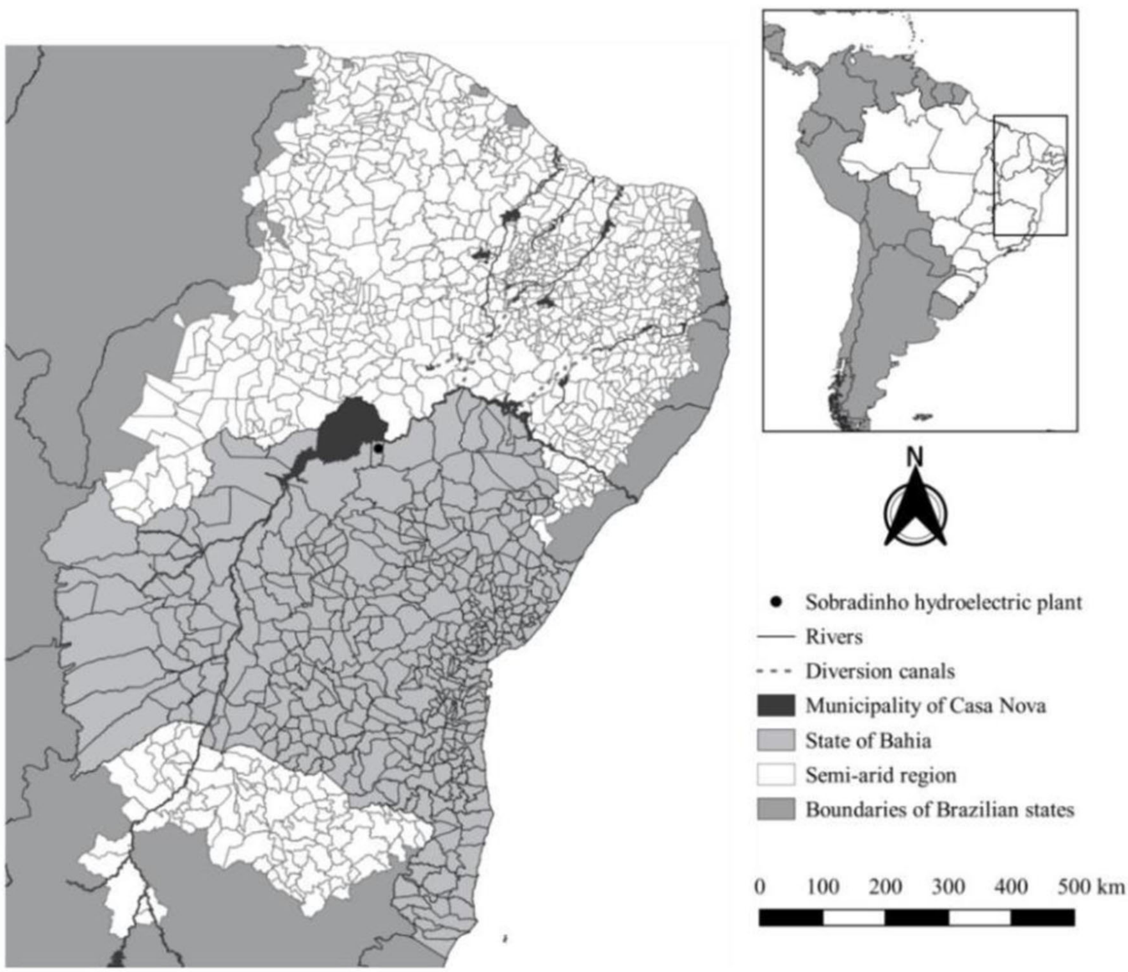

FIGURE 2 | Location of the Municipality of Casa Nova.

food systems via environmental education, introduction of endogenous production techniques, and transition to agroecology (Brasil, 2018). The state governments in Brazil are in charge of its definition and implementation. In Bahia, policymakers opted for outsourcing this service to NGOs and other private entities, which are contracted through public calls.

Land Regularization

In Brazil, the land regularization is arranged at the state government's discretion. In 2013, the State of Bahia launched a plan (Law 12.910) aiming at regularization of public lands in rural areas that have been occupied by traditional communities. This law provides for a contract regarding the right of land usufruct for up to 90 years, with the possibility of renewal for an equal period.

THE STUDY AREA: RAINFED FOOD SYSTEM AND THE *FUNDO DE PASTO* COMMUNITIES

Our case study site is situated in the municipality of Casa Nova, belonging to the semi-arid region of the state of Bahia (Brazil). High temperatures and droughts are characteristic of the region, which features annual average rainfall and temperature of 800 mm and 25.4° C, respectively (Casa Nova, 2019). Its aridity relates to spatiotemporal precipitation concentration, with 71% of rainfall occurring between January and April (FUPEF, 2007). In addition, the rate of evaporation of 3,000 mm/year is three times higher than the precipitation (Malvezzi, 2007).

The Municipality of Casa Nova covers an area of 9.697 km² and is home to 64,940 inhabitants, 42% of whom reside in rural areas (IBGE, 2010). While the municipality is close to the São Francisco River (as seen in **Figure 2**), farmers do not use the water from the river for irrigation due to the lack of suitable infrastructure.

Local semi-arid agriculture is mainly rainfed, dominated by small traditional agriculture and livestock for family consumption and trade. The main activities consist of small animal husbandry (e.g., goats, sheep, free-range chickens, and pigs), annual crop cultivation (e.g., onions, beans, cassava, maize) and agro-extractivism (medicinal plants, native fruits, and vegetables). Common locally processed foods include cheese, juices, sweets, jams, cakes, cookies, tapioca, cassava pudding, etc. The sale of fresh, stored, or processed foods occurs in two different ways: (1) autonomously, via direct sale to middleman, or via local markets; or (2) collectively, via associations, or cooperatives whereby family-farm goods are pooled together and sold.

The *fundo de pasto* communities have adopted rainfed food system techniques to make a living. The main feature of the *fundo de pasto* communities is that of communal land, which is used for extensive animal rearing (Garcez, 1987), combined with individual areas for family crop growing (Cotrin, 1991). Three communities took part in the present study, Melancia, Riacho Grande, and Ladeira Grande. **Table 1** shows the key characteristics of each community.

TABLE 1 | Main features of the *fundo de pasto* communities participating in this study.

Community	Total number of families	Size of land occupied (hectares)
Melancia	42	600
Riacho grande	211	12,000
Ladeira grande	60	2,500

METHODOLOGY

The present study employed a qualitative approach to generate knowledge on people's perceptions, behavior, experiences, and interactions (Pathak et al., 2013). This can provide detailed information and resources for researchers to challenge other dominant or naturalized socio-economic and political concepts and understandings (Patton, 2002). We used content analysis to examine and quantify our qualitative data, thereby identifying, coding, and classifying topics and patterns from our interviews and questionnaires (Downe-Wamboldt, 1992). Collected data also were interpreted using descriptive statistics (Woodrow, 2014).

Fieldwork was conducted in three municipalities of the semi-arid region: Casa Nova, Petrolina, and Juazeiro. The communities of *fundo de pasto* that took part in the study are located in the municipality of Casa Nova. Petrolina and Juazeiro, neighboring municipalities to Casa Nova, are home to urban centers that host NGOs, government institutions, universities, etc. Because we also interviewed people from these institutions, we included Petrolina and Juazeiro in the course of our fieldwork.

The *fundo de pasto* communities of Melancia, Riacho Grande, and Ladeira Grande were selected for the study based on the following criteria: (1) importance of the rainfed food system to the socio-economic development of the semi-arid region; (2) good access of communities to food public policies; (3) previous contacts with a community member who enabled us to link up to and interact with local families—traditional communities are often closed to outsiders.

During fieldwork, our data collection included participatory observation, focus groups, semi-structured interviews, and questionnaires. We took notes and made audio recordings. We organized six focus groups with community members, each involving 4–12 farmers. Additionally, 11 semi-structured interviews were conducted with academics and representatives from NGOs, social movements, and private and public institutions[2]. Finally, questionnaires were conducted with 54

[2]The institutions that participated in this study break down as follows: Brazilian Agricultural Research Corporation (*Empresa Brasileira de Pesquisa Agropecuária*, EMBRAPA), Food and Nutrition Security National Council (*Conselho Nacional de Segurança Alimentar e Nutricional*, CONSEA), Regional Institute for Appropriate Small Farming and Animal Husbandry (*Instituto Regional da Pequena Agropecuária Apropriada*, IRPAA), Advisory Service for Rural People's Organizations (*Serviço de Assessoria a Organizações Populares Rurais*, SASOP), *Pró-Semiárido*, Pastoral Land Commission (*Comissão Pastoral da Terra*, CPT), Agrarian Development Coordination (*Coordenação de Desenvolvimento Agrário*, CDA) and Secretariat for the Promotion of Racial Equality (*Secretaria de Promoção da Igualdade Racial do Governo do Estado da Bahia*, Sepromi). We also

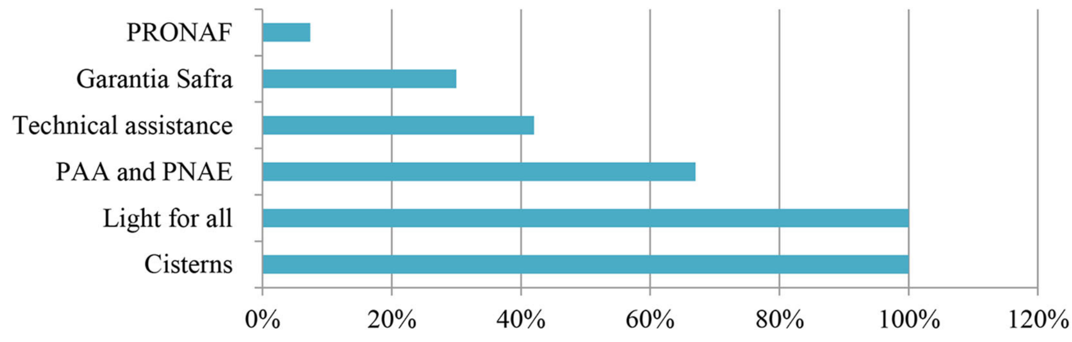

FIGURE 3 | Families' participation in the programmes.

families from the *fundo de pasto* communities located in the municipality of Casa Nova (18 families per community).

Concerning the sampling method for the questionnaire application, families were selected using the following criteria: (1) self-recognition as *fundo de pasto* members; (2) belonging to one of the communities selected for the study (Melancia, Ladeira Grande or Riacho Grande); and (3) presence of an adult (regardless of gender) identifying as the head of the family. We prioritized local leaders to answer the questionnaires because they were more involved in policy procedures and more aware of community needs. From the total respondents, 34% were community leaders and the remainder were regular family farmers. For the focus groups, participants also needed to belong to one of the three communities and be available to participate in our discussions and share experiences and information from a qualitative point of view with the researchers. For the focus groups, we invited community farmers, local leaders, and elderly people who were knowledgeable about historical community events and the dynamics of the rainfed food system. Data collection was oriented around the qualitative research methods, with the main goal that of capturing detailed information, regardless of the number of participants.

The focus groups, strategically, were carried out prior to implementation of the questionnaires. This enabled us to use the information gathered in these collective reflections to design consistent questions and obtain more precise information from families. The public policies considered in our study were selected by the focus group participants, as were the guiding topics we discussed in the six meetings. The topics participants chose for the focus groups' debates became indicators, as follows:

- Production practices
- Market structure
- Food security
- Land access.

interviewed two academics and accessed publicly available data on policies and programmes from government websites, statistical institute, Brazilian Institute of Geography and Statistics (*Instituto Brasileiro de Geografia e Estatistica*, IBGE) and the government think tank Institute for Applied Economic Research (*Instituto de Pesquisa Econômica Aplicada*, IPEA).

RESULTS

In this section, we analyse—from stakeholders' perspectives—policy effects on food system activities (input provision, producing, processing, trading, and consuming), considering related impacts on production practices, market structures, food security, and land access. **Figure 3** shows the degree of families' participation in each programme, based on data from questionnaires.

Policy Impacts on Production Practices (Access to Credit, Technology, and Knowledge)

The *Garantia Safra* is a compensation mechanism granted by the federal government in times of proven harvest loss due to weather events (e.g., drought), serving as an emergency financial aid (SEAD, 2018). Only 16 families (30%) reported having received such compensation. They received an average of about R$ 850 (currently US$ 257) to compensate for harvest losses. These families used the money to buy food, make home repairs, and purchase inputs such as machinery and animal feed. While only 30% reported having received the grant, all families claimed to have lost part of their harvest. **Figure 4** shows the reasons why families did not access the *Garantia Safra* financial support.

Only four families managed to access the PRONAF credit, (∼7.4%). The credit was invested in productive activities such as purchase of animals, purchase of inputs, or improvements to property infrastructure like small repairs (e.g., fixing fences, adjusting roof of the house). The remaining 50 families that never accessed the credit opportunity explained their non-participation in the programme by mentioning the reasons illustrated in **Figure 5**.

Access to credit and financial support for production was very limited among the families. However, when comparing the two programmes, we noted that PRONAF beneficiaries were fewer in number than *Garantia Safra* beneficiaries, as seen in **Figure 6**.

During the focus groups, participants indicated their perception of a geographical distinction in the distribution of the credit—one that strongly favors states in Brazil's southern region where there is a concentration of capitalized family farming. In terms of budget, the programme saw an increase from R$ 38 billion in 1996 to R$ 165 billion in 2016 (BCB, 2017). However, the uneven geographical distribution of credit is confirmed by the fact that, between 2013 and 2017, family farmers in the state of Bahia received 4% of the total programme budget while family farmers in the state of Rio Grande do Sul received 15% (IBGE, 2017). Despite receiving a smaller amount of credit, the state of Bahia accounts for 15% of the total rural properties in Brazil, while the state of Rio Grande do Sul accounts for only 7% of the total (IBGE, 2017).

Regarding technologies, the cisterns were indicated by participants as the most important technology-related policy in terms of mitigation of the effects of drought. Photovoltaics were also cited as a significant technological advance, but not one that significantly changed food system activities. All 54 families participating in the survey benefited from the cisterns (P1MC) and "Light for All."

The cisterns enabled storage and consumption of rainwater. Previously, people collected unsuitable water from dams located far from the communities. Farmers stated that the cisterns enabled them to diversify their production by facilitating cultivation of a variety of fruits and vegetables. All respondents agreed that the cisterns helped to increase their production; 73% of the interviewed families already grew vegetables and fruits before the cisterns; 82% of the families believed that the diversification of production led to improvements in family consumption and food security; 93% of the interviewed families stated that they increased their consumption of fruits and vegetables.

Most of the fruits previously consumed were collected from wild plants. However, after installation of the cisterns, families began cultivating some of these wild fruits on their farms. **Table 2** shows the diversity of fruits and vegetables before and after the cisterns.

The cisterns' efficiency depends on the availability of rainfall throughout the year. As reported by the participants in focus groups, due to recurrent droughts the water in the cistern runs out in certain periods of the year, forcing families to rely on government assistance for water supplies. To improve people's autonomy regarding water access, one academic interviewed recommended implementation of water adductor systems to connect the communities to the São Francisco River.

According to participants, access to energy has always been limited in the rural areas of the Casa Nova municipality. Despite

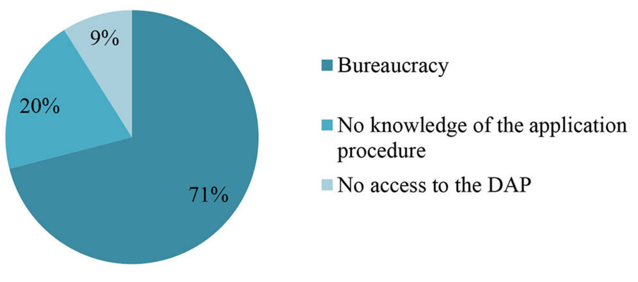

FIGURE 4 | Main reasons why farmers did not access *Garantia Safra*.

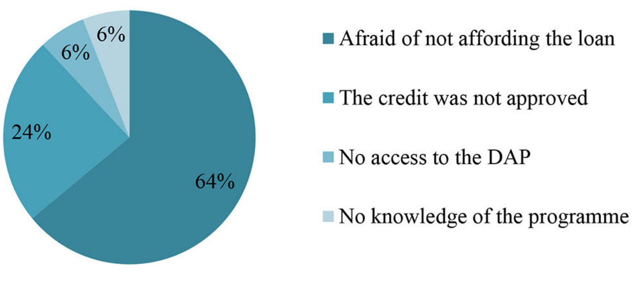

FIGURE 5 | Main reasons why farmers did not access PRONAF.

TABLE 2 | Crops cultivated before and after installation of cisterns.

Cultivated crops	
Before the cisterns	**After the cisterns**
Vegetables	**Vegetables**
Lettuce, onion, tomato, kale, corn, sweet potato, and cassava	Lettuce, onion, tomato, kale, corn, sweet potato, cassava, chili, chives, parsley, okra, gherkin, pepper, cucumber, arugula, pumpkin, carrot, and beetroot
Fruits	**Fruits**
Umbu, mango, *seriguela*, orange, tangerine, guava, passion fruit, banana starfruit, *cajá*, coconut, and cashew	*Umbu**, mango, *seriguela**, orange, tangerine, guava*, passion fruit, banana, starfruit*, *cajá**, cashew*, soursop, pineapple, coconut, *acerola*, papaya, and lemon

**formerly collected as wild plants, now cultivated.*

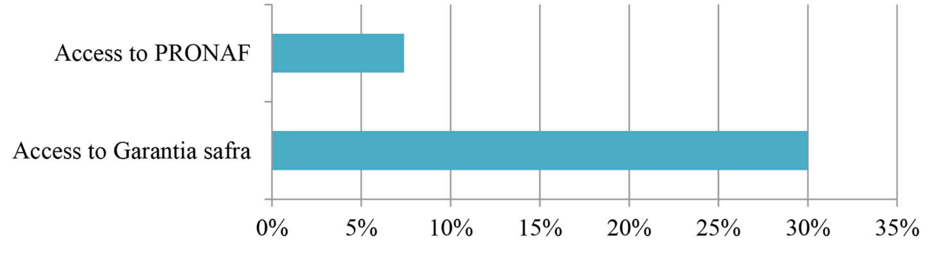

FIGURE 6 | Percentage of families that accessed PRONAF or *Garantia Safra*.

being located 50 km from the *Sobradinho* hydroelectric power plant (see **Figure 2**), the rural communities that participated in this study do not have access to electrical grid networks. Instead, photovoltaic technology became an alternative to enable access to electricity.

All families who answered the questionnaire had a domestic photovoltaic system featuring a solar panel but no energy storage. Solar panel capacities are 40–50 W, enabling use of low-voltage devices, such as portable radios, televisions, and cell phones. However, use of larger electronics, such as refrigerators, is not possible. The impossibility of refrigerating food was cited by 92% of the families as one of the biggest limitations to their photovoltaic systems. Due to such difficulties in storing food, farmers cannot trade goat milk and must make cheeses daily that keep longer in uncooled environments. The following statement, captured in a focus group, describes household use of photovoltaic systems:

"Solar energy has replaced the oil lamp and that was great, but the *umbu* processing unit and the pudding factory run on diesel-powered generators. We have machinery, but we have no energy. Equipment is not used due to a lack of energy. During the *umbu* season, we process the fruit to make the pulp, which needs to be taken immediately to the urban center to be frozen. The costs get very high this way. Sometimes it makes production almost impossible" (informant 1, a farmer of the Ladeira Grande community, who participates in PAA).

Finally, concerning access to knowledge, 42% of the participants benefited from NGOs' technical assistance, subcontracted by the State of Bahia. Local NGOs develop projects to improve environmental education, food security, and agricultural practices. Environmental education includes discussions of sustainable solutions to cope with the semi-arid climate. Regarding food security, the NGOs assist farmers and associations with applying for public calls to participate in the PNAE (National School Feeding Programme) and PAA (Food Procurement Programme). Concerning agricultural practices, the projects involve assistance with soil management, creation of a seed bank, and preservation of the region's characteristic biome (*Caatinga*). The NGOs also encourage the transition to agroecology through the use of organic matter as a natural fertilizer (thus avoiding use of chemical fertilizers).

The families domesticate seeds by selecting the most adapted and productive varieties. Participants spoke about the importance of the seed bank and its role in preserving local biodiversity and avoiding genetic erosion, especially in critical periods of drought. Regarding soil management, participants highlighted the importance of knowing techniques that enable coexistence of multiple crops, such as beans and corn cultivated on the same land. By diversifying production and maintaining soil productivity, they avoid exhausting soils.

Regarding the transition to agroecology, farmers reported that certain agroecological techniques have long been applied in the communities, for example fertilization of greens and vegetables with animal dung; chickens are fed part of the corn planted on farms and, where kept, pigs are fed part of the domestic food and crop waste. Nonetheless, they indicated that despite their good prior knowledge of certain techniques, outside technical assistance helps to improve them based on scientific findings. Many participants reported that the technical assistance enabled them to understand the benefits of agroecological practices that they applied intuitively, providing insights into how they work to maintain a resilient environment.

One of the problems identified by the communities was that by outsourcing the technical assistance service, the number of family farmers receiving support had fallen. Participants stated that when the state government provided the service in the past, it covered more families. They said that the institutions that replaced the state in this function have a limited budget, which translates into less coverage. Participants pointed out that since some families were not informed and properly guided regarding the procedures and bureaucratic steps involved in applying for contracts, they had difficulties accessing public policies.

Policy Impacts on Market Structure

Accessing markets is one of the challenges faced by *fundo de pasto* families in Casa Nova, due to both geographical distance to urban centers and lack of economies of scale. Approximately 67% of the families ($N = 36$) sell their production through the PAA (Food Procurement Programme) and PNAE (National School Feeding Programme). The remaining 18 families that were not part of these programmes belong to the Riacho Grande community. This community is known for being resistant to dialogue with the government due to previous violence related to disputes over accessing land. Usually, they market their products directly to middlemen, and less frequently, trade via local markets.

Before the PAA and PNAE, trading involved middlemen or local markets. Both options fluctuated throughout the year, as sales depended above all on the purchasing power of locals. The main changes around the programmes were the creation of an alternative market for family farmers' products, at a fair price. According to one of the focus group participants, the agreement between the community association and the municipality/state regarding goat supplies set the price of live animals[3] at R$ 14.00 per kg (∼US$ 3.45 per kg for an adult animal weighing around 12 kg; the total price would be US$ 41.4). By contrast, middlemen usually paid only half this price. All families that answered the questionnaire raised goats as their main economic activity and source of income. **Figure 7** shows how families market goats.

Our study found that the PAA and PNAE programmes strongly encouraged cooperativism and associativism among the members of the communities. Cooperatives and associations generally enable more efficient organization of family farmers, helping them cope with the difficulties imposed by highly competitive and challenging market structures. Strategically, these forms of work organization enable economies of scale by multiplying production to meet the demands of PAA and PNAE contracts, without increasing costs. Moreover, by participating in these collective organizations, farmers have more opportunities to obtain agricultural inputs that they cannot access individually. All families that answered the questionnaire participated in

[3]When the animal is sold to the government, through the institutional market, it is alive. The government is in charge of taking the animal to a slaughterhouse that follows the rules of municipal health surveillance.

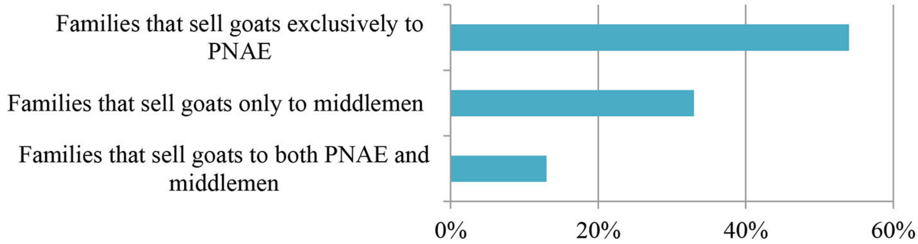

FIGURE 7 | The ways in which families market goats.

associations of small rural producers and 66% were integrated in cooperatives.

In addition, the families that traded their products via the PAA and PNAE perceived more advantages in the institutional market for two main reasons: price stability and household income. Since prices are set in advance for the entire duration of the contract, farmers do not suffer the downsides of price fluctuations that are typical of agricultural markets. Also, with the guaranteed market, family farmers increased their opportunities for income generation, leading to household financial stability.

Similar to the cisterns, the PAA and PNAE also encouraged farmers to diversify their production. A remarkable example of this process was described by one of the participants who reported that the *umbu*, a very typical and abundant fruit of the semi-arid region, was not commercially exploited by the community before the programmes. However, thanks to the programmes, they were motivated to cultivate *umbu* to produce juice, pulp, and jelly. Another example is cassava pudding, a community-created recipe that was offered to the programmes for school meals.

PAA and PNAE became the main source of agricultural income for most of the participating families. On the one hand, it means that they have access to a stable source of income; on the other hand, it indicates a strong dependence of farmers on the programmes. To reduce this dependency on institutional markets, additional financial resources could be applied to diversify farmers' agro-processing activities, encouraging them to produce value-added goods from raw materials that are usually discarded, such as goat leather. Also, the communities could invest in logistics to diversify their market opportunities and sell products to new consumers.

Policy Impacts on Food Security

Income instability used to be one of the major concerns of farmers before the food procurement programmes (PAA and PNAE), especially due to the difficulty of marketing. Inconsistent monthly income was associated by participants with vulnerability to food insecurity. Income is important to food security because farmers need off-farm food to satisfy their dietary needs in quantity and variety (e.g., salt, couscous, sugar, cooking oil, rice, etc.), despite producing an important amount of food themselves. Droughts were also cited as an aggravating factor contributing to food insecurity.

Farmers indicated that the PAA (Food Procurement Programme) played a decisive role in addressing food insecurity in times of drought, thanks to food provisioning. Information collected through questionnaires revealed that 33% of the interviewees received cassava and 25% received beans from the programme between 2005 and 2009, when there was a severe drought. Both products were produced by other communities that did not suffer significant consequences from the droughts.

One topic raised repeatedly by participants was the desire to become self-sufficient in terms of food production at the household level. Participants emphasized the lack of public policies that encourage on-farm food-production autonomy. Despite this, they expressed satisfaction knowing that kids from the communities—and also those enrolled in public schools in the municipality of Casa Nova—had access to good quality food through the PNAE. They indicated that before the PNAE children were fed canned and processed foods supplied by large industrial food companies. According to the participants, children now have access to fresh fruits, vegetables, and other healthy foods produced by local family farmers.

Finally, participants expressed concern about their further participation in policymaking processes following cessation of the Food and Nutrition Security National Council (*Conselho Nacional de Segurança Alimentar e Nutricional*, CONSEA) in January 2019. The purpose of the council was to link policymakers and society to enhance food security policies. According to a CONSEA representative, cessation of the council harms local democracy, as the body was created to encourage participatory public policy design.

Policy Impacts on Land Access

The members of the three communities under analysis expressed dissatisfaction with the Law 12.910 of the State of Bahia, launched in 2013, which granted land usufruct for a limited number of years. Participants reported that they have rights to this land and, for this reason, they claim deserve land titles, not simply an authorization to occupy the land for a certain period. They also stated that accepting the contract meant confirming the premise that the land does not belong to them, as dictated by the state government.

Importantly, people's connection to the land goes beyond productive needs related to their food system. Participants stated that the notion of territoriality is essentially linked to people's identity, manifesting the interweaving of culture and nature. In this way, having access to and control over land enables these communities to reduce their food insecurity, to increase their income stability, and to maintain relationships with nature consistent with cultural identities built up over time.

As reported by interviewees, the communities' land struggles began in the 1970s when the federal government built the *Sobradinho* hydroelectric dam, flooding an area of 4,214 km^2 and displacing approximately 12,000 families, including some of the study participants. Currently, they occupy the land of the municipality of Casa Nova or "New Home." The dam construction set a precedent for land grabbing in the region. Land grabbing is an old practice in Brazil, typically beginning with irregular occupation of land, supported by fraud and falsification of property titles. In 1979, there was an intense and violent conflict between the communities and a company that illegally occupied their lands for cattle raising. Families were displaced, farmers were threatened with death, and a community leader was murdered. Nowadays, communities fear losing their lands to wind power companies, agribusinesses, and mining companies, which have been advancing in the region with the collusion of the government of Bahia[4].

Links Between Food Policies and Rainfed Food System Activities

The public policies affected food system activities (input provision, production, processing, trading/selling, and consumption) and communities in different ways. In this section, we will summarize what was reported by the participants regarding public policies, highlighting which policies contributed most to food system activities and communities in terms of financial stability, food security, and cooperativism, as shown in **Figure 8**.

According to the perceptions of farmers, the *Garantia Safra* (financial support), cisterns (enabling access to water), and the technical assistance were the public policies that contributed the most to input provision. Farmers viewed these programmes as helping to diversify production, reduce water insecurity, and adopt agro-ecological production practices. By contrast, the rural credit programme—especially the PRONAF—was seen as structurally flawed, very restricted in scope, and overly bureaucratized.

According to participants, the cistern and public food procurement programmes (PAA and PNAE) contributed to the diversification and growth of production, especially of vegetables and fruits. Technical assistance also played an important role in production and processing, by providing knowledge support for more conscious and efficient use of resources. However, the food system would be more efficient if there were enough electricity to meet the demands of the communities concerning food processing and storage.

[4]The government of Bahia implemented a series of measures to attract investments, including offering concessions of state land for industrial and agricultural use and energy production; offering reductions and exemptions from state taxes, and offering low-interest financing (FIEB, 2019; SEI, 2019).

Both trading and consumption were driven by the PAA and PNAE programmes through increased marketing capacity for small-scale farmers. They were equally important for food security by creating food stocks for public nutrition programmes and by providing school meals. Thanks to the guaranteed market and long-term contracts, farmers finally achieved some income stability, which translated into food security. The main issue now is their economic dependence on the public institutional markets, with most of their household income coming from the public food procurement programmes.

The combination of public policies led to complementary outcomes in the food system. For instance, crop diversification related to cisterns and the public food procurement programme also led to improved quantity and quality of production on behalf of community families, schools, and groups. However, some public policies stood out more than others, exhibiting more contributions to the performance of the food system. According to the interviews, focus groups, and questionnaires, the most successful policies were those that affected not one, but several interrelated food system activities. In this sense, the PAA and PNAE played a fundamental role in linking input provision, production, processing, trading, and consuming.

The main community benefits from the food public policies relate to financial stability, food security and cooperativism. The institutional market opened up space for commercialization of goods produced by the communities. Further, the guaranteed market, fixed prices, and reliable long-term contract arrangements stabilized incomes for the families, aiding household financial planning. This new reality is completely different from the previous situation, in which families were caught—on uncertain terms–between middlemen, local markets, and supermarket contracts. Indeed, the PAA and PNAE represent possible solutions to the communities' historical trading difficulties, effectively improving household resilience and food security. Another great benefit of the food procurement programmes for the communities has been the encouragement they provide toward cooperativism and collective sales. Marketing organized through cooperatives and associations brought together a significant number of family farmers, enabling creation of economies of scale. Regardless of the institutional market, communities are now organized and prepared to market their production at local, regional, and national levels, with greater consistency.

However, land regularization remains an unsolved dilemma, as the proposal for the right of usufruct of the land for 90 years was rejected by the communities due to the conditional terms of access to land. Communal lands are fundamental to the communities' main economic activity and source of income (goat rearing), demanding large expanses of land. Further, the territory is interwoven with the culture and identity of the communities, whose connections with the land go beyond aims of capital reproduction. Above all, as long as the communities lack land titles they remain vulnerable to displacement, especially in light of the recent advance of capital in these areas and the frequency of land grabbing. According to Germani (2010), expansion of capital and increases in demand for land in

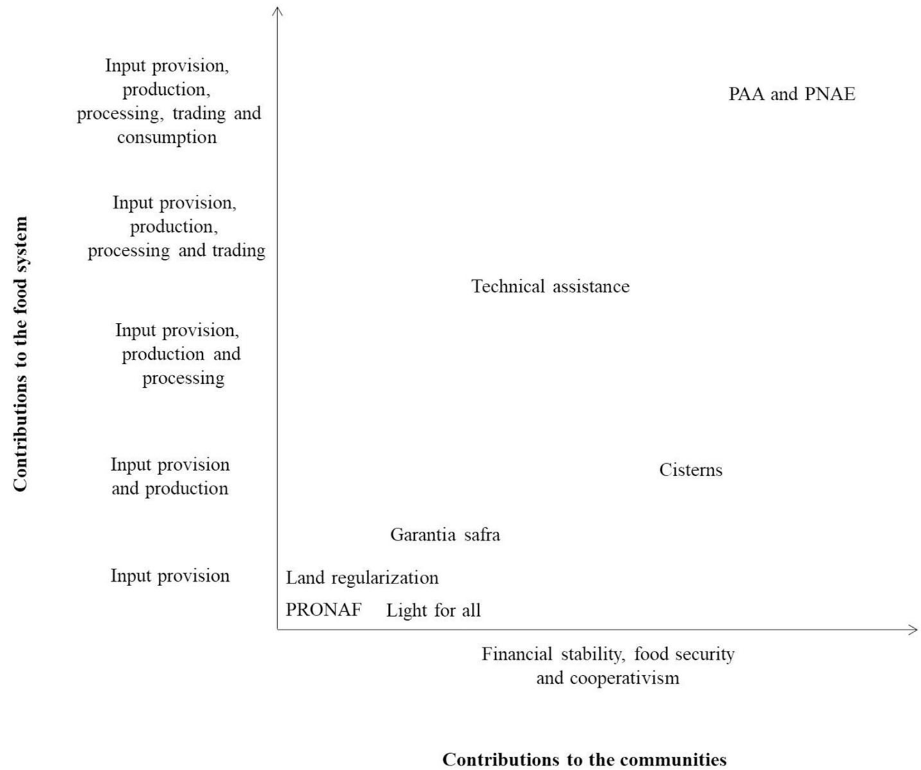

FIGURE 8 | Contribution of food public policies to the food system and communities.

semi-arid areas has made the spaces occupied by traditional communities valuable to outsiders, attracting the attention of various companies. According to the author (ibid.), government measures to attract capital in rural areas—such as tax exemption, credit extension, and flexible labor laws—have contributed to the "territorialization" of capital and the "deterritorialization" of family farmers.

DISCUSSION

Our research emerges from a critical perspective on "productivist" agricultural development, highlighting the inconsistencies of this model that emphasizes technological intensification and expansionary production (Stiglitz, 2007). Productivist-oriented food systems reinforce inequalities and injustices in rural and urban areas (Dias, 2014). More comprehensive food public policies are needed to build sustainable food systems. They must apply holistic approaches to improve input provision, production, processing, trading/selling, and consumption, and aim at provision of year-round access to food that meets people's nutritional needs (FAO, 2014). Further, public policies are fundamental to ensure respect for human rights, labor standards, and promote duties of preserving environmental integrity (Rist and Jacobi, 2016).

The present study examined family farmers' perception of positive and negative impacts of food policies on their food system. Participants felt that the integrated set of public policies enabling family farmers' participation in markets and those disseminating technology and knowledge had positive effects on the sustainable socio-economic development of the rural economy and food security. Farmers' increased access to institutional markets enabled communities' to sell their goods at fair prices, generating stable incomes and better family livelihoods. Public food procurement programmes (PAA and PNAE) made the greatest contribution to the performance of the food system, improving the areas of input provision, production, processing, trading, and consuming. The PAA and PNAE also enabled economies of scale, while reducing food insecurity at the household and community levels. The technical assistance programme was also highly relevant, serving to aid the dissemination of agroecological practices, promote techniques for soil management (less chemical fertilizer use), build a community-based bank of selected seeds for crop diversification, and promote the conservation of biodiversity and local ecosystems. Finally, the increased access to water enabled by cisterns helped communities achieve water security, while boosting diversification of production.

However, the food public policies also exhibited contradictions and flaws. One of the major problems is the policies' broad approach, which fails to attend to the specific needs of the heterogeneous and socially diverse categories of family farmers in Brazil (Schneider and Nniederle, 2008). For instance, the credit offered by PRONAF for rural activities is unequal in its geographical distribution, appearing to favor capitalized family farmers located in the south of Brazil. Farmers also cited obstacles such as excessive bureaucratization and lack of orientation regarding application procedures, which harm the effectiveness of the credit and financial support policies (PRONAF and *Garantia Safra*). With respect to technical assistance programmes, the photovoltaic systems provided in the "Light for All" intervention do not support use of devices that demand high-voltage energy, such as refrigeration equipment that would benefit the food system. Finally, the failure to resolve land titling/tenure issues points to deep structural constraints that are hindering the medium- to long-term resilience of the communities in terms of food security, cultural identity, and preservation of the ecosystem. Ongoing territorial disputes (due especially to land grabbing) threaten the existence of the *fundo de pasto* communities who are strongly connected to the land.

CONCLUSION

In conclusion, our assessment of the perceived impacts of public food policies on rainfed farming in Bahia reveals opportunities as well as challenges. Several recommendations regarding public food policies emerge from our analyses, and could serve as starting points for further policy discussion and scientific study.

First, with respect to the rural credit granted via PRONAF, we recommend reformulating the programme's budget distribution based on the quantity of rural properties existing in each state. Second, the technical assistance programme should strive to better inform farmers about credit application, streamline its procedures, and reduce bureaucracy. Third, local access to energy could be improved by expanding the grid network to reach communities and supply them with reliable electricity. Fourth, to reduce their dependence on public food procurement programmes (PAA and PNAE), farmer associations and cooperatives could invest part of their financial resources in diversifying production and adding more value through processing activities, therewith expanding their marketing options.

In addition, the *fundo de pasto* communities expressed their concrete desire to produce enough food for self-consumption. This would require new policies that encourage and support on-farm food production and consumption. Finally and crucially, stable long-term access to land is fundamental to conserve the rainfed food system, enable maintenance of specific territorialities, protect the environment, ensure high quality nutrition, and protect the rights of traditional communities. In this sense, there is an urgent need for fair distribution and democratization of the land, enabling emancipatory development of the communities and sustainability.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR'S NOTE

Food security, access to market, land, knowledge, and means of production are challenges for traditional family farmers, located in the Brazilian semi-arid region. Historically traditional family farmers were neglected by the Brazilian State, however, from 1950/60s onwards the shift away from the "Green Revolution" and productivist model triggered a rural development paradigm change toward sustainability. The new comprehensive socio-economic and environmental food policies targeted at family farmers caused profound changes in the ways of how this group are integrated into Brazilian society. The lack of studies that interpret the farmers perspective of the impacts promoted by public policies on their food system motivated us to develop this study, aiming to fill this research gap. The stakeholder perspective on public policy is an indicator for interpreting social transformation processes and assessing the actor's subjective motivations and political involvement. Also, social participation and inclusion contribute to the monitoring of public policies, besides of being fundamental to the representation of collective interests. Through this paper the claims and the recommendations of the traditional family farmers were formally organized and analyzed, serving as a basis for the improvement of world wile public policies.

AUTHOR CONTRIBUTIONS

EB and SR: conceptualization and methodology. EB and TS: data collection. EB: formal analysis and writing–original draft preparation. SR: supervision. All authors have read and agreed to the published version of the manuscript.

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REFERENCES

Abramovay, R. (1992). *Paradigmas do Capitalismo Agrário em Questão*. São Paulo: Hucitec/ANPOCS/Ed, Unicamp.

Albers, H. J., Lee, K. D., and Sims, K. S. (2018). Economics of habitat fragmentation: A review and critique of the literature. *Int. Rev. Environ. Resour. Econ.* 11, 97–144. doi: 10.1561/101.00000092

Altieri, M. A. (1995). *Agroecology: The Science of Sustainable Agriculture*. Boulder: Westview Press, Boulder.

Aquino, J. R., and Schneider, S. (2015). "O Pronaf e o desenvolvimento rural brasileiro: avanços, contradições e desafios para o futuro," in *Políticas Públicas de Desenvolvimento Rural No Brasil*, eds C. Schneider, and S. Grisa *Porto Alegre (Brasil: UFRGS)*, 53–81.

BCB (2017). *Rural Credit Data Matrix (MDCR). Banco Central do Brasil*. Available online at: https://dadosabertos.bcb.gov.br/dataset/matrizdadoscreditorural (accessed November 04, 2019).

Belik, W. (2010). *Desenvolvimento Rural e Segurança Alimentar: Contribuições Teóricas Para o Desenho e Avaliação de Políticas Públicas*. Institute of economics, UNICAMP.

Berkes, F., Colding, J., and Folke, C. (2002). *Navigating Social-Ecological Systems: Building Resilience for Complexity and Change*. Cambridge: Cambridge University Press.

Borlaug, N. E., and Dowswell, C. R. (2003). "Feeding a world of 10 billion people: a 21st century challenge," in *Paper Presented at the International Congress 'in the Wake of the Double Helix: From the Green Revolution to the Gene Revolution* (Bologna), 27–31.

Brasil (2009a). *Lei no 11.947, de 16 de junho de 2009*. Brasília: Congresso Nacional.

Brasil (2009b). *Ministério de Minas e Energia. Manual de Operacionalização do Programa Nacional de Universalização do Acesso e Uso da Energia Elétrica. Anexo à Portaria n. 85, de 20 de Fevereiro de 2009*. Brasília: Programa Luz Para Todos.

Brasil (2011). *Decreto No 7.535, de 26 de julho de 2011. Institui o Programa Nacional de Universalização do Acesso e Uso da Água - "ÁGUA PARA TODOS"*. Brasília: Congresso Nacional.

Brasil (2012). *Decreto No 7.775, de 4 de Julho de 2012. Regulamenta o Art. 19 da Lei No 10.696, de 2 de Julho de 2003, Que Institui o Programa de Aquisição de Alimentos, e o Capítulo III da Lei no 12.512, de 14 de Outubro de 2011, e dá Outras Providências*. Brasília: Congresso Nacional.

Brasil (2018). *Assistência Técnica e Extensão Rural*. Available online at: http://www.agricultura.gov.br/assuntos/ater (accessed January 08, 2020).

Casa Nova (2019). *O Município. Prefeitura de Casa Nova*. Available online at: http://www.casanova.ba.gov.br/detalhe-da-materia/info/a-cidade/6501 (accessed October 15, 2019).

Colonna, P., Fournier, S., and Touzard, J. M. (2013). "Food systems," in *Food System Sustainability: Insights From DuALIne*, eds R. E. Esnouf, M. B. Russel, and N. Bricas (Cambridge: Cambridge University Press), 69–100.

CONAB (2016). *Companhia Nacional de Abastecimento*. Available online at: http://www.conab.gov.br/ (accessed November 12, 2019).

Cotrin, D. V. N. (1991). *O Pastoreio Comunitário em Uauá: Uma Expressão da Subordinação do Trabalho Ao Capital*. (Master thesis), Salvador: Ciências Sociais, UFBA.

de Schutter, O. (2010). *Countries Tackling Hunger with a Right to Food Approach: Significant Progress in Implementing the Right to Food at National Scale in Africa, Latin America and South Asia*. Geneva: United Nations.

de Schutter, O. (2014). The specter of productivism and food democracy. *Wisconsin Law Rev.* 2014, 199–233. Available online at: https://wlr.law.wisc.edu/volume-2014-no-2/

Del Grossi, M. E. (2019). *Políticas Públicas Diferenciadas Para A Agricultura Familiar No Mercosul Ampliado: O Caso do Brasil*. Brasília: COPROFAM/CONTAG.

Dias, J. (2014). *A Possível Transição Para Agricultura Ecológica*. Outras palavras. Available online at: https://outraspalavras.net/sem-categoria/a-possivel-transicao-para-uma-agricultura-ecologica/ (accessed December 21, 2019).

Downe-Wamboldt, B. (1992). Content analysis: method, applications, and issues. *Health Care Women Int.* 13, 313–321. doi: 10.1080/07399339209516006

Ericksen, P., Bohle, H., and Steward, B. (2010). "Vulnerability and resilience of food systems," in *Food Security and Global Environmental Change*, eds J. S. I. Ingram, P. J. Ericksen and D. M. Liverman (London: Earthscan), 67–77. Available online at: https://cgspace.cgiar.org/handle/10568/3593

FAO (1996). *Rome Declaration on World Food Security and World Food Summit Plan of Action. World Food Summit 13-17 November 1996*. Rome: FAO

FAO (2006). *The State of Food Insecurity in the World, 2006: Eradicating World Hunger, Taking Stock 10 Years after the World Food Summit*. Rome: FAO.

FAO (2009). *Towards Improved Land Governance*. Rome: FAO Land Tenure Working Paper, 11.

FAO (2010). "Sustainable diets and biodiversity. Directions and solutions for policy, research and action," in *Proceedings of the International Scientific Symposium: Biodiversity and Sustainable Diets United Against Hunger*. Rome: FAO Headquarters. Available online at: http://www.fao.org/docrep/016/i3004e/i3004e.pdf

FAO (2014). "Rome declaration on nutrition," in *Second International Conference on Nutrition* (Rome: FAO).

FAO (2018). *Sustainable Food Systems: Concept and Framework*. Rome: FAO.

FAO (2019a). *Global Sustainable Development Report 2019: The Future is Now—Science for Achieving Sustainable Development*. New York, NY: FAO.

FAO (2019b). *The State of Food Security and Nutrition in the World*. Rome: FAO.

FIEB (2019). *Serviço de Apoio ao Investidor Estudo Setorial—Energias Renováveis na Bahia*. Available online at: http://www.fieb.org.br/midia/2017/6/ESTUDOSETORIALCINENERGIASRENOVAVEIS.PDF (accessed February 14, 2020).

FUPEF (2007). *Apoio Técnico e Institucional Para o Desenvolvimento do Programa Florestal da Chapada do Araripe em Pernambuco. Produto 2 – Diagnóstico*. Curitiba: Governo do Estado de Pernambuco/CODEVASF/MMA.

Garcez, A. N. R. (1987). *Fundo de Pasto: Um Projeto de Vida Sertanejo*. Salvador: INTERBA/SEPLANTEC/CAR.

Germani, G. I. (2010). "Questão agrária e movimentos sociais: a territorialização da luta pela terra na Bahia," in *(GEO) Grafias Dos Movimentos Sociais. Feira de Santana (BA)*, eds A. S. Coelho Neto, E. M. C. Santos, and O. A. Silva (Feira de Santana: UEFS Editora), 269–304.

Grisa, C., and Schneider, S. (2015). "Três gerações de políticas públicas para a agricultura familiar e formas de interação entre sociedade e Estado no Brasil," in *Políticas Públicas de Desenvolvimento Rural No Brasil*, eds C. Schneider and Grisa, S. Porto Alegre (Brasil: UFRGS), 19–50.

Huang, J., Pray, C., and Rozelle, S. (2002). Enhancing the crops to feed the poor. *Nature* 418, 678–684. doi: 10.1038/nature01015

IBGE (2010). *Censo Demográfico 2010*. Rio de Janeiro: Instituto Brasileiro de Geografia e Estatística.

IBGE (2017). *Censo Agropecuário 2017*. Rio de Janeiro: Instituto Brasileiro de Geografia e Estatística.

ILC (2010). *Links Between Land Tenure Security and Food Security*. Rome: International Land Coalition.

Kay, S., Mattheisen, E., McKeon, N., De Meo, P., and Moragues Faus, A. (2018). *Public policies for food sovereignty. Think piece series Food for Thought No.1*. Amsterdam, Rome, and Heidelberg: Hands on the Land/FIAN/Terra Nuova/TNI

Landesa (2012). *Land Rights and Food Security. The Linkages Between Secure Land Rights, Women, and Improved Household Food Security and Nutrition*. Seattle: Issue brief: Land rights and food security.

Malvezzi, R. (2007). *Semi-Árido - Uma Visão Holística*. Brasília: CONSEA.

MDA (2019). *Base de Dados do Crédito Pronaf*. Brasília: Ministério do Desenvolvimento Agrário.

MDS (2017). *Programa Cisternas: Boletim Informativo No 005*. Brasília: Ministério do Desenvolvimento Social.

Paschoal, A. D. (1995). Modelos sustentáveis de agricultura. *Agric. Sustentável* 1, 11–16.

Pathak, V., Jena, B., and Kalra, S. (2013). Qualitative research. *Perspect. Clin. Res.* 4:192. doi: 10.4103/2229-3485.115389

Patton, M. Q. (2002). *Qualitative Research and Evaluation Methods, 3 Edn*. London: Sage.

Paul, E. (1993). 'Limits to growth' and 'sustainable development': grappling with ecological realities. *Ecol. Econ.* 8, 269–288. doi: 10.1016/0921-8009(93)90062-B

Peraci, A. S., and Bittencourt, G. A. (2011). "Family farming and price guarantee programs in brazil: the food acquisition program (PAA)," in *Fome Zero: The*

Brazilian Experience, eds J. G. Silva, C. G. França, and M. E. Del Grossi (Brasília: MDA/FAO), 193–224.

Perrucci, R., and Perrucci, C. (2014). The good society: core social values, social norms, and public policy. *Soc. Forum.* 29, 245–258. doi: 10.1111/socf.12078

Phipps, R. H., and Park, J. R. (2002). Environmental benefits of genetically modified crops: global and European perspectives on their ability to reduce pesticide use. *J. Anim. Feed Sci.* 11, 1–18. doi: 10.22358/jafs/67788/2002

Piesse, J., and Thirtle, C. (2010). Agricultural R&D, technology and productivity. *Philos. Trans. R Soc. London Series B Biol. Sci.* 365, 3035–3047. doi: 10.1098/rstb.2010.0140

Prasifka, J. R., Hellmich, R. L., and Weiss, M. J. (2009). "Role of biotechnology in sustainable agriculture," in: *Integrated Pest Management. Concepts, Tactics, Strategies and Case Studies,* eds E. B. Radcliffe, W. D. Hutchison, and R. E. Cancelado (Cambridge: Cambridge University Press), 260–272.

Rastoin, J. L., and Ghersi, G. (2010). *Le Système Alimentaire Mondial. Concepts et Méthodes, Analyses Et Dynamiques.* Versailles: Editions Quæ.

Rist, S., and Jacobi, J. (2016). *Selection of Food Systems in Bolivia and Kenya and Methods of Analysis.* Bern: Centre for Development and Environment (CDE), University of Bern

Rocha, C. (2007). Food insecurity as market failure: a contribution from economics. *J. Hunger Environ. Nutr.* 1, 5–22. doi: 10.1300/J477v01n04_02

Sabourin, E. (2007). Que política pública para a agricultura familiar no segundo governo Lula? *Sociedade e Estado* 22, 715–751. doi: 10.1590/S0102-69922007000300009

Sambuichi, R. H. R., Kaminsk, R., Perin, G., Moura, I. F., Januário, E. S., Mendonça, D. B., et al. (2019). *Programa de aquisição de alimentos e segurança alimentar: modelo lógico, resultados e desafios de uma política pública voltada ao fortalecimento da agricultura familiar*. Discussion paper. Brasília: Ipea.

Santos, F. P. (2011). *Coalizões de Interesses e A Configuração Política Da Agricultura Familiar No Brasil. Escola de Administração de Empresas de São Paulo.* Rio de Janeiro: Fundação Getúlio Vargas.

Schneider, S., and Nniederle, P. A. (2008). "Agricultura familiar e teoria social: a diversidade das formas familiares de produção na agricultura," in *Savanas: Desafios E Estratégias Para O Equilíbrio Entre Sociedade, Agronegócio E Recursos Naturais,* eds F. G. Faleiro, A. L. Farias Neto (Planaltina: Embrapa Cerrados), 989–1014.

SEAD (2018). *Plano Safra da Agricultura Familiar 2017-2020.* Brasília: Secretária Especial de Agricultura Familiar e Desenvolvimento Agrário.

SEI (2019). *Análise & Dados.* Available online at: http://www.sei.ba.gov.br/phl8/download/p024190.pdf (accessed February 14, 2020).

Sidaner, E., Balaban, D., and Burlandy, L. (2013). The Brazilian school feeding programme: an example of an integrated programme in support of food and nutrition security. *Public Health Nutr.* 16, 89–94. doi: 10.1017/S1368980012005101

Silva, S. P. (2011). *Políticas públicas, Agricultura Familiar e Desenvolvimento Territorial.* São Paulo, 16, 126–144.

Soratto, J., and Witt, R. R. (2013). Participação e controle social: percepção dos trabalhadores da saúde da família. *Texto Contexto Enferm.* 22, 89–96. doi: 10.1590/S0104-07072013000100011

Stiglitz, J. E. (2007). *Globalização: Como Dar Certo*. São Paulo: Companhia das Letras.

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., and Polasky, S. (2002). Agricultural sustainability and intensive production practices. *Nature* 418, 671–677. doi: 10.1038/nature01014

Wezel, A., Bellon, S., Doré, T., Francis, C., Vallod, D., and David, C. (2009). Agroecology as a science, a movement or a practice: a review. *Agron Sustain. Dev.* 29, 503–515. doi: 10.1051/agro/2009004

Woodrow, L. (2014). "Presenting descriptive statistics," in *Writing about Quantitative Research in Applied Linguistics,* eds L. Woodrow (London: Palgrave Macmillan).

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frontiers in Sustainable Food Systems

REVIEW
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Maintaining Diversity of Integrated Rice and Fish Production Confers Adaptability of Food Systems to Global Change

Sarah Freed[1], Benoy Barman[2], Mark Dubois[3], Rica Joy Flor[4], Simon Funge-Smith[5], Rick Gregory[6], Buyung A. R. Hadi[4], Matthias Halwart[7], Mahfuzul Haque[2], S. V. Krishna Jagadish[8], Olivier M. Joffre[9], Manjurul Karim[3], Yumiko Kura[1], Matthew McCartney[10], Manoranjan Mondal[11], Van Kien Nguyen[12,13], Fergus Sinclair[14,15], Alexander M. Stuart[16], Xavier Tezzo[3,17], Sudhir Yadav[18] and Philippa J. Cohen[19]*

[1] WorldFish, Phnom Penh, Cambodia, [2] WorldFish, Dhaka, Bangladesh, [3] WorldFish, Yangon, Myanmar, [4] Sustainable Impact Platform, International Rice Research Institute, Phnom Penh, Cambodia, [5] Food and Agriculture Organization of the United Nations, Bangkok, Thailand, [6] Independent Consultant, Yangon, Myanmar, [7] Food and Agriculture Organization of the United Nations, Rome, Italy, [8] Kansas State University, Manhattan, KS, United States, [9] Agence Française de Développement, Phnom Penh, Cambodia, [10] International Water Management Institute, Colombo, Sri Lanka, [11] Sustainable Impact Platform, International Rice Research Institute, Dhaka, Bangladesh, [12] An Giang University, Vietnam National University, Ho Chi Minh City, Vietnam, [13] Fenner School of Environment & Society, The Australian National University, Canberra, ACT, Australia, [14] World Agroforestry (International Centre for Research in Agroforestry, ICRAF), Nairobi, Kenya, [15] School of Natural Sciences, Bangor University, Wales, United Kingdom, [16] Sustainable Impact Platform, International Rice Research Institute, Bogor, Indonesia, [17] Environmental Policy Group, Wageningen University, Wageningen, Netherlands, [18] Sustainable Impact Platform, International Rice Research Institute, Los Banos, Philippines, [19] WorldFish, Penang, Malaysia

Edited by:
Barbara Gemmill-Herren, Prescott College, United States

Reviewed by:
Didier Bazile, Institut National de la Recherche Agronomique (INRA), France
Luis F. Goulao, University of Lisbon, Portugal

***Correspondence:**
Sarah Freed
s.freed@cgiar.org

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Rice and fish are preferred foods, critical for healthy and nutritious diets, and provide the foundations of local and national economies across Asia. Although transformations, or "revolutions," in agriculture and aquaculture over the past half-century have primarily relied upon intensified monoculture to increase rice and fish production, agroecological approaches that support biodiversity and utilize natural processes are particularly relevant for achieving a transformation toward food systems with more inclusive, nutrition-sensitive, and ecologically sound outcomes. Rice and fish production are frequently integrated within the same physical, temporal, and social spaces, with substantial variation amongst the types of production practice and their extent. In Cambodia, rice field fisheries that strongly rely upon natural processes persist in up to 80% of rice farmland, whereas more input and infrastructure dependent rice-shrimp culture is expanding within the rice farmland of Vietnam. We demonstrate how a diverse suite of integrated production practices contribute to sustainable and nutrition-sensitive food systems policy, research, and practice. We first develop a typology of integrated production practices illustrating the nature and degree of: (a) fish stocking, (b) water management, (c) use of synthetic inputs, and (d) institutions that control access to fish. Second, we summarize recent research and innovations that have improved the performance of each type of practice. Third, we synthesize data on the prevalence, outcomes, and trajectories of these practices in four South and Southeast Asian countries that rely heavily on fish and rice for food and nutrition security. Focusing on changes since the food systems transformation brought about by the Green Revolution, we illustrate how integrated production practices continue to serve a variety of objectives to varying degrees: food and nutrition security, rural livelihood diversification and income improvement, and biodiversity conservation. Five shifts to support contemporary food system transformations [i.e., disaggregating (1) production practices and (2) objectives, (3) utilizing diverse metrics, (4) valuing emergent, place-based innovation, (5) building adaptive capacity] would accelerate progress toward Sustainable Development Goal 2, specifically through ensuring ecosystem maintenance, sustainable food production, and resilient agricultural practices with the capacity to adapt to global change.

Keywords: food systems, integrated agri-aquaculture, inland fisheries, food security, food policy

INTRODUCTION

The world's food systems are simultaneously overreaching planetary boundaries and failing to meet nutritional needs (Gordon et al., 2017; Willett et al., 2019). In response, transformation of current food systems is increasingly called on to minimize environmental impacts and sustain livelihoods while also producing food of sufficient quantity and quality to meet the growing needs and demands of populations globally (Ericksen et al., 2010; IPES-Food, 2016; Schipanski et al., 2016). A food system incorporates "*all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation, and consumption of food, and the outputs of these activities, including socio-economic and environmental outcomes*" (HLPE, 2014). Transformation toward more sustainable and equitable food systems is a foundation of the Sustainable Development Goals, directly for the second goal "Zero Hunger" and as a critical enabler of many of the other goals (Caron et al., 2018). To re-shape food systems to meet the environmental, economic, and social challenges of sustainability, we must shift away from a narrow productivity focus that dominated previous "revolutions" in agriculture (Pingali, 2012; Blesh et al., 2019), aquaculture (Troell et al., 2014), and fisheries (Ratner and Allison, 2012).

Agroecological practices are important in the package of solutions needed to transform food systems (IPES-Food, 2016; HLPE, 2019) and to build resilience of livelihoods and landscapes in the face of global change (Sinclair et al., 2019). Agroecological practices are diverse, but can be characterized by a generic set of agroecological principles, such as a preferential use of natural processes and a focus on local suitability, equity, and systems management (Altieri, 2002; HLPE, 2019). The principles are conceptualized in categories of technical and/or biophysical and of organizational, institutional and/or socio-economic attributes (Therond et al., 2017; AFD CIRAD, 2018) and their application occurs in varying degrees along a gradient (HLPE, 2019). These gradients can be used to develop a typology that organizes and describes the diversity of practices within a production sector, e.g., maize and livestock production in central United States (Blesh and Wolf, 2014). A typology of production practices can guide evaluation of the contribution of various practices to food systems objectives (Blesh and Wolf, 2014) and facilitate planning for transformation pathways to sustainable food systems. We demonstrate this approach in the context of Asian agricultural landscapes and diets, which have been dominated by rice and fish for more than a millennium (Ruddle, 1982; Miao, 2010).

Rice cultivation occurs in a range of agroecosystems, including lowland areas that are seasonally inundated by rainfall and floodplains extending from the edges of rivers and lakes (Heckman, 1979; Fernando, 1993). These agroecosystems also provide habitats for a "*wide range of aquatic species (including finfish, crustaceans, mollusks, reptiles, insects, amphibians, and aquatic plants) used for consumption and/or sale*" (FAO, 2014). Rice-fish production practices (RFPPs) are those where the cultivation of rice takes place while allowing the simultaneous or rotational presence of: naturally occurring fish and other aquatic species that are harvested through fisheries; and/or introduced fish populations that are cultured (FAO, 2014). Throughout Asia, RFPPs have developed, persisted, and been transformed under a range of environmental, social, and agricultural policy contexts and comprise diverse fish species and rice varieties (e.g., Heckman, 1979; Halwart, 1998; Amilhat et al., 2009). Presence of fish within agri-food systems is observed globally (Halwart and Gupta, 2004) and is especially important in food insecure nations (Fisher et al., 2017). Despite this, incorporation of fish in agricultural food security programs is lacking (Fisher et al., 2017) and fish are rarely more than anecdotally mentioned in agroecology and food systems literature, despite their relative resource efficiency among animal sources of dietary protein and rich micronutrient content for diets (Kawarazuka and Béné, 2011; Béné et al., 2015).

In addition to the production of rice and fish for food and nutrition, RFPPs can provide a range of ecosystem services and farmer benefits, depending on the approach and application of agroecological principles. For example, RFPPs can make efficient use of scarce water and land resources (Frei and Becker, 2005), maintain biodiversity (Liu et al., 2013; Freed et al., 2020), regulate water flows and water quality (Zhang et al., 2012), and reduce the need for agrochemicals for rice production (Halwart, 1994; Cheng-Fang et al., 2008; Xie et al., 2011). RFPPs can also provide local food and nutrition security (Garaway et al., 2013; Halwart, 2013), income benefits (Hortle et al., 2008), generate more revenue per hectare than rice monoculture (Dwiyana and Mendoza, 2006), and produce higher rice yields (Halwart and Gupta, 2004; Dubois et al., 2019), although rice monoculture can be more cost and labor efficient (Dwiyana and Mendoza, 2006) and in some contexts, the economic return from fish replacing a rice crop in a rotational system can be lower than the return from the second rice crop (Ahmed et al., 2011). RFPPs are not the only agroecological alternatives to rice monoculture: ecologically engineered farm design can enhance biodiversity and ecosystem function (Horgan et al., 2016); and alternate wetting and drying can reduce water and input use in irrigated systems (Tirol-Padre et al., 2018).

The nutritional, environmental, and cultural value of integrated rice and fish production has been recognized in contemporary agricultural discussions since the 1948 convening of the FAO Rice committee (Halwart and Gupta, 2004). However, interest in RFPPs has periodically waxed and waned, and has yet to gain traction alongside the more locked-in monoculture production focus (Halwart and Gupta, 2004; IPES-Food, 2016). This is at least in part due to the disciplinary approaches to agricultural and aquatic systems research and development that impedes integration among crops and wild and cultured aquatic resources (Amilhat et al., 2009; Tezzo et al., 2020). Currently, agricultural investments increasingly seek to achieve food and nutrition security as well as environmental sustainability objectives (Asian Development Bank, 2015; McCartney et al., 2019), leading to increased interest in agroecological approaches (e.g., FAO, 2019; HLPE, 2019). To assist in these efforts, we describe the range of RFPPs and evidence of their respective advantages, constraints, and contributions toward sustainable food systems outcomes. This focus is particularly urgent, given that the types of RFPPs that actively stock, enclose, and feed fish are expanding in China and elsewhere in Asia (Hu et al., 2015; Miao, 2016; FAO, 2019), without consideration of other types of RFPPs that are more aligned with agroecological principles.

To bridge the evidence gap constraining decision-making, we draw on literature to develop a typology to distinguish RFPPs based on the nature and degree of: water infrastructure and management, the use of inputs, the source of fish populations, and the institutions that control access to fish. We illustrate these variations across four RFPP types for which we also highlight current and potential research and innovation to improve delivery of food system outcomes (specifically, food and nutrition security, equitable and secure incomes, and ecological integrity). We review the trajectory of RFPPs in four case studies from South and Southeast Asian countries and examine the enabling and constraining factors determining the contributions of each RFPP to food systems objectives. We discuss how RFPPs might contribute to different pathways for food system transformation in rice producing nations, and explore ways in which research, innovation and policy might enable achievement of multiple food system objectives.

RICE-FISH PRODUCTION PRACTICE TYPOLOGY

Rice-fish production practices vary substantially between different contexts and countries. Scholars have noted distinctions based on biophysical and technical attributes such as relative use of naturally occurring or stocked fish, water control measures, intensity, and volumes of production inputs (e.g., Welcomme and Bartley, 1998; Koohafkan and Furtado, 2004) and organizational and institutional attributes such as the fit with, and use of, a range of governance institutions (e.g., Dey et al., 2013). Drawing on literature and field observations, we developed a typology of RFPPs along an agroecological continuum. The continuum runs from high levels of human control and substitution of natural processes to lower levels of control and greater reliance on natural processes for five variables; (1) fish stocks, (2) water control, (3) inputs to support fish production, (4) inputs for rice, and (5) institutions that control access to fish (**Figure 1**). Rice varieties, fish species, water access, and rice planting methods are also variable, but do not help to distinguish RFPPs as they vary as much (or more) within types than between them. The typology is not meant to be an exhaustive catalog of all factors that vary and all types of RFPPs, but instead aims to elucidate at a broad level distinguishing characteristics that influence RFPP performance in terms of food systems outcomes. The typology is also not meant to impose a "good-better-best" ordering of production practices, as RFPP suitability is highly context dependent. In addition, differing contexts and drivers of change can also result in variable outcomes within each RFPP type. In this sense, RFPPs are only one component necessary for delivering food systems objectives. Below, we describe in greater detail each exemplar RFPP in terms of the five aforementioned attributes.

Rice Field Fisheries

Rice field fisheries lie on the "natural" end of the agroecological continuum. Rice field agroecosystems often contain both rice fields and water bodies such as canals, streams, ponds, and ditches. The harvest or capture of naturally occurring (or "wild") fish, aquatic animals, and plants from these rice field agroecosystem habitats is referred to as "rice field fisheries" (Gregory, 1997). An important contributing factor to these fisheries is the natural inundation of rice fields that occurs following seasonal rainfall and/or rising water levels in rivers and other water bodies. During the inundation period, many fish and other aquatic species migrate from perennial water bodies to the shallow rice field wetlands to feed and spawn. Studies on the aquatic biodiversity of rice field fisheries across China and Southeast Asia reveal that between 32 and 147 species are caught and used (**Supplemental Table 1**; **Supplemental Figure 1**). Flood waters and fish may be considered a common pool resource even when occurring in privately owned rice fields. Wild fish are most prevalent when water management infrastructure (dikes and irrigation) and agrochemical use is minimal (Ali, 1990). Stocking may occur in rice field fisheries, but if it does occur is usually minimal. Small water bodies within or near the rice field may be managed as perennial refuges for fish, or may function as trap ponds from which fish are harvested when the pond is pumped or dries out.

Historically, rice field fisheries were the most widespread form of integrated rice and fish production (Coche, 1967; Ruddle, 1982), and are most common in rainfed and deepwater rice growing areas (Vo, 1975; Gregory, 1997). Rice field fisheries

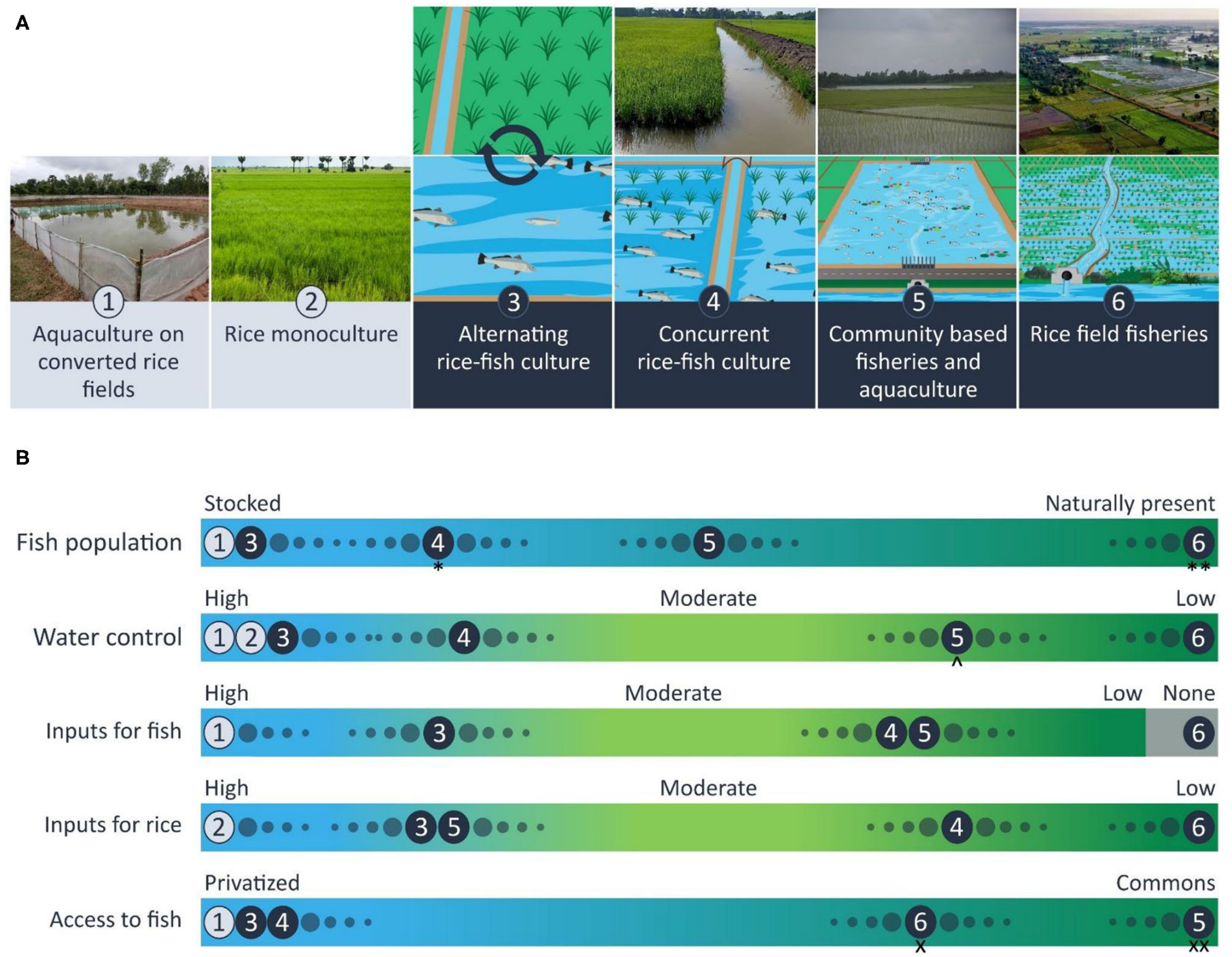

FIGURE 1 | Typology of rice-fish production practices with **(A)** illustrations and photos that depict each of four exemplars (3–6) and their monoculture reference points (1,2). **(B)** The types can be distinguished by use of agroecological attributes along a continuum of (high to low) control and substitution of natural processes in terms of; (1) fish stocks, (2) water control, (3) inputs to support fish production, (4) inputs for rice, and (5) institutions that control access to fish. Notes: *May include some naturally present; **May include some stocking; ^Water control is low during monsoon season and fish production, but irrigation is used during dry season for rice cultivation; ×May include privatization of fish remaining in ponds within rice fields after flood recession; ××Commons for small wild fish harvest, contractual shared access for cultured and wild fish.

have been an important source of food and nutrition security, and livelihoods for rural communities in low and middle income countries across Asia, including in Bangladesh (Dey et al., 2013), Cambodia (Freed et al., 2020), Lao PDR (Nguyen Khoa et al., 2005; Garaway et al., 2013), Myanmar (Gregory, 2017), and Vietnam (Berg et al., 2017; Nguyen et al., 2018). The level of formal recognition and management support for these fisheries varies greatly, with the greatest support occurring in Cambodia (e.g., Fisheries Administration, 2011; MAFF, 2014). While rice field fisheries are a long-standing RFPP, associated agricultural and water use practices and infrastructure have changed substantially in many places. Community fish refuges (Kim et al., 2019) and "fish friendly" irrigation (Baumgartner et al., 2016) are two examples of contemporary rice field fisheries research and innovations for improving environmental connectivity, biodiversity conservation, and food and water security.

Community-Based Fisheries and Aquaculture

Community-based fisheries and aquaculture straddles the intervention and natural ends of the agroecological continuum. This practice emerged out of three decades of research in Bangladesh on floodplain aquaculture and community-based fisheries management (Sheriff et al., 2010) and was introduced and adapted in Vietnam, Cambodia, Mali, and China, but was not as widely adopted or expansive as in Bangladesh (Joffre and Sheriff, 2011). Community-based fisheries and aquaculture occurs in lowland flood-prone areas where one crop of rice is grown only during dry months. During the monsoon, rice fields are inundated to a depth of 2–3 m. The resulting inundated water bodies were traditionally common areas to harvest wild fish and aquatic plants. Under community-based fisheries and aquaculture, the water bodies are managed for both wild fish and fish culture through technical and water governance innovations that allow wild fish (and fishers) to remain while introducing a communal governance model for cultured fish production (Joffre and Sheriff, 2011). For example, inlets and outlets are fenced to keep cultured fish in while allowing passage for smaller wild fish. Community-based fisheries and aquaculture includes stocking the water body with fish; most commonly cultured fingerlings of carp species (e.g., *Hypophthalmichthys molitrix, Labeo rohita*), but also wild-sourced broodfish of mola (*Amblypharyngodon mola*), other small indigenous species such as darkina (*Esomus danricus*), chela (*Chle phulo*), puntius (*Puntius* spp.), and indigenous species of catfish (*Clarias* spp.) and snakehead (*Channa* spp.). Ongoing social (e.g., water governance), economic (e.g., market connections and resilience), and ecological (e.g., optimal stocking densities and biodiversity) innovations continue to be tested and refined in Bangladesh.

Rice-Fish Culture

Rice-fish culture lies predominantly on the intervention end of the agroecological continuum, yet comprises a broad range with many variations in practice. Rice-fish culture is the deliberate introduction of fish from cultured or wild sources into a rice field. While some practices may include natural water flows to retain wild stocks and biodiversity, these are recused in areas with greater water control and physical barriers to prevent escape of cultured fish (Lu and Li, 2006). Water is actively managed to control inflow during the dry season, and dikes are used in the wet season to prevent flooding. In many contexts, rice-fish culture is privately managed by the rice farmers who own or lease the plot of land.

There are two main sub-types: concurrent culture and alternating culture. Concurrent culture is where rice and fish are cultivated together in the same space and at the same time. Alternating culture is where production cycles of rice and fish crops are sequential. It is possible for both concurrent and alternating culture to take place within the same rice plot, as in extended growing seasons for fish beyond the rice harvest, or multiple crops of fish with fewer crops of rice (e.g., Halwart and Gupta, 2004; Dwiyana and Mendoza, 2008). Input use is often determined by the extent of intensification and the timing and duration of the fish culture (Halwart and Gupta, 2004). Fish are often fed when present at high densities and for fish grow-out, while low densities of fish and/or short duration fish culture are likely to require either no inputs or only the application of fertilizers to promote phytoplankton growth and enhance the natural food web that supports fish (Halwart and Gupta, 2004).

Concurrent Rice-Fish Culture

In concurrent culture, also referred to as rice fish co-culture, the rice field is modified with the addition of small water bodies such as trenches, small ponds, or depressions that retain water for fish habitat when water levels become low in the rice field. Concurrent culture tends to use fewer agrochemical inputs than alternating culture or rice monoculture and aquaculture. Fish can feed from the biodiversity in the flooded rice field and have a symbiotic relationship with rice crops; fish are eating insects and so reduce the pest load, and fish waste contributes nutrients to the water and soil. Concurrent rice-fish culture requires a relatively high degree of management, for water levels in the rice field and the fish shelter through irrigation and dikes. A drop in water levels in the rice field can undesirably shorten the duration of fish culture, especially toward the end of a monsoon season or as water availability declines during a dry season. In Asia, rice fish co-culture has been practiced for over a 1,000 years, with documented cases in China, Indonesia, Thailand, Vietnam, Philippines, Malaysia, Bangladesh, and Myanmar (Halwart and Gupta, 2004). Recent innovations for this long-standing practice focus on diversifying production through fish polyculture and integrated (i.e., plant and vegetable) farming (FAO, 2019).

Alternating Rice-Fish Culture

Alternating culture of rice and fish allows the use of crop-specific inputs during both rice and fish culture. The use of inputs for both fish and rice is relatively common, and as such alternating culture is considered an intensive form of rice-fish culture. During fish culture, the rice field is managed as a shallow pond for fish. Feed and other inputs may be used to maintain and grow fish. Alternating culture also occurs in coastal areas, such as the "gher" in Bangladesh and rice-shrimp culture in Vietnam, in which a monsoon season rice crop is followed by a dry season shrimp crop that coincides with saline water intrusion in the rice field. Production of fish fingerlings in alternating culture has emerged as aquaculture growth has boosted the demand for fingerlings, particularly in Indonesia (Costa-Pierce, 1992) and Bangladesh (Barman and Little, 2006). Recent research investigates technical and social innovations that might improve institutional arrangements among stakeholders and across scales (Joffre et al., 2018; Nguyen et al., 2020). A primary focus of this research is to improve management of organic and agrochemical effluents from culture ponds and rice cropping (Joffre et al., 2018).

FISH, RICE, AND FOOD SYSTEM TRANSFORMATION

The Green Revolution and transformation of rice culture into intensively farmed monoculture began in Asia around 55 years ago (Hazell, 2009; Pingali, 2012). The changes to farming practices included increased use of agrochemicals and more rigid control of water flows and storage that reduced connectivity to floodplains and water bodies (e.g., Shankar et al., 2005; Tong, 2017). Resultant gains in rice production were substantial; across all developing countries rice yields increased 109% (Pingali, 2012), and across Asia total rice production rose steadily and rice prices decreased (Hazell, 2009). However, these farming practices also resulted in losses of long-standing integrated rice and fish production in, at least, Malaysia (Ali, 1990), Vietnam (Berg et al., 2017), and China (Lu and Li, 2006). In Bangladesh, Cambodia, Vietnam, and Myanmar, rice yield per hectare doubled between

1965 and 2000 and rice production tripled by 2013 (FAO, 2020c). Rapid growth in aquaculture production occurred around the same time globally (Troell et al., 2014) and across Asia (Ahmed and Lorica, 2002).

While these agriculture and aquaculture revolutions gained substantial investment and policy attention, inland capture fisheries persisted, but were underappreciated and largely ignored (Cambodia is a notable exception). Recent research illustrates the magnitude of inland capture fisheries contributions to food and nutrition security (Fluet-Chouinard et al., 2018). Yet, the low profile of inland fisheries in national and global policies, including their absence in the Sustainable Development Goals, persists to this day (Cooke et al., 2016; Funge-Smith and Bennett, 2019). This is most likely due to a combination of factors, including the difficulty of collecting reliable data to fulfill official statistics (Coates, 2002; Bartley et al., 2015), the popular crisis narrative of declining fisheries (Friend et al., 2009), and of the fact that fisheries are not easily amended to the Green Revolution approach of increasing productivity. This lack of policy support for fisheries greatly reduces the nutrition provision potential of food systems (Thilsted et al., 2016).

Current conditions are ripe for transformation in Asia's rice and fish sectors, yet there are multiple interpretations about what this transformation might entail. Rice producing regions are now contending with issues of climate change (Johnston et al., 2009) and factors exacerbating persistent rural poverty, such as increasing indebtedness and loss of land (Ingalls et al., 2018). Local, regional, and international demand for rice and fish are expected to increase for decades to come (Reardon and Timmer, 2014; Chan et al., 2017). Fish demand is tracking faster than population growth, with increases in per capita consumption associated also with rising incomes (Chan et al., 2017). Rice demand is expected to continue to grow as populations do, but at a slower rate given that as incomes rise, diets tend to diversify away from staples (Reardon and Timmer, 2014; Cramb and Newby, 2015). Growth in both rice and inland capture fishery production have recently slowed or reversed in the case study countries. Rice production seems to have peaked in Myanmar (in 2009) and Vietnam (in 2015) and production growth is slowing in Bangladesh and Cambodia (since 2010; FAO, 2020c). Inland capture fisheries production has begun to level off or gradually decline (since 2009 for Bangladesh, 2013 for Cambodia, 2016 for Myanmar, and 2001 for Vietnam; FAO, 2020a). As of 2013, capture fisheries still contributed substantially to inland fish production in Bangladesh (36%), Cambodia (86%), and Myanmar (49%; FAO, 2020a). While growth in aquaculture production has continued, the relative contributions of inland capture fisheries remain sizeable in terms of fish production (Edwards et al., 2019; Funge-Smith and Bennett, 2019), food provision (Arthur and Friend, 2011; Fluet-Chouinard et al., 2018), and nutrition (Halwart, 2006; Kawarazuka and Béné, 2011; Thilsted et al., 2016; Golden et al., 2019).

The Green Revolution aim of increased rice production was adopted to varying degrees in Bangladesh, Cambodia, Myanmar, and Vietnam. Yet, the cases below (illustrated in **Figures 2–6**) illustrate how each country also adopted different objectives and strategies for food system transformation, including different policies, investments, and institutions that influenced the various roles RFPPs played. For each country we examine: (1) the changes to RFPPs and the trajectory of rice and fish sectors since 1980; (2) prevalent RFPPs, innovations, and evidence of RFPP contributions to food systems objectives; and (3) current gaps to achieving food system objectives and the potential pathways for rice and fish production to address these challenges.

Cambodia

Rice field fisheries have been maintained, initially as consequence of socio-political crisis, but more recently through deliberate policy recognizing their importance as a productive fishery, their provision of food and nutrition security, the cultural appreciation of wild sourced foods, as well as the difficulty to compete with already advanced aquaculture in neighboring countries. Regaining food self-sufficiency was Cambodia's initial food system objective following the Khmer Rouge crisis, while a longer-term objective has been to employ the large rural population. Rice and fisheries contributed to Cambodia's substantial GDP growth from the 1990s, although the contribution from these sectors has declined in recent years (The World Bank, 2017a).

Rice field fisheries are prevalent in Cambodia's 2.6 million hectare wet season rice landscape, due to relatively little irrigation (17% of total area) and expansive rainfed lowlands (80% of total area; MAFF, 2017, 2018) with relatively little flood control. Official estimates place rice field fisheries at 30% of national inland fisheries production, while field-based studies estimate a higher contribution equivalent to 60–70% (Chheng et al., 2016; Freed et al., 2020). It is estimated that more than 50% of Cambodian rural households engage in fishing at least occasionally (Nasielski et al., 2016). Cambodia law stipulates that wild aquatic species in flooded rice landscapes are a common pool resource available to anyone who chooses to fish, provided non-destructive gear is used as stipulated by law. At least 150 wild aquatic species are present within the rice field landscape of Cambodia's Tonle Sap Region, including finfish, snakes, frogs, bivalves, prawn, crab, turtle, waterbirds, insects, and aquatic plants (Freed et al., 2020). The majority of aquatic species are used for food, and in sum these fisheries can provide more than 60% of the fish and other aquatic animals consumed within local farming-fishing households (Freed et al., 2020).

Cambodia's government has formally recognized, in the form of an enhancement strategy, the values and potential of rice field fisheries for national food production and food and nutrition security (Fisheries Administration, 2011; CARD, and TWG-SP&FS, 2014). The enhancement strategy centers around scaling community fish refuges, which are perennial water bodies (i.e., a small pond or part of a large reservoir) that provide habitats for fish within the rice field landscape (**Figure 3**). Research and pilots implemented throughout the Tonle Sap region have informed the development of best management practices for community fish refuges, including co-management, community engagement, and fisheries management strategies as well as habitat improvement and conservation measures (Kim et al., 2019).

One of Cambodia's primary food system challenges is to ensure more secure farming livelihoods, as evidenced by the

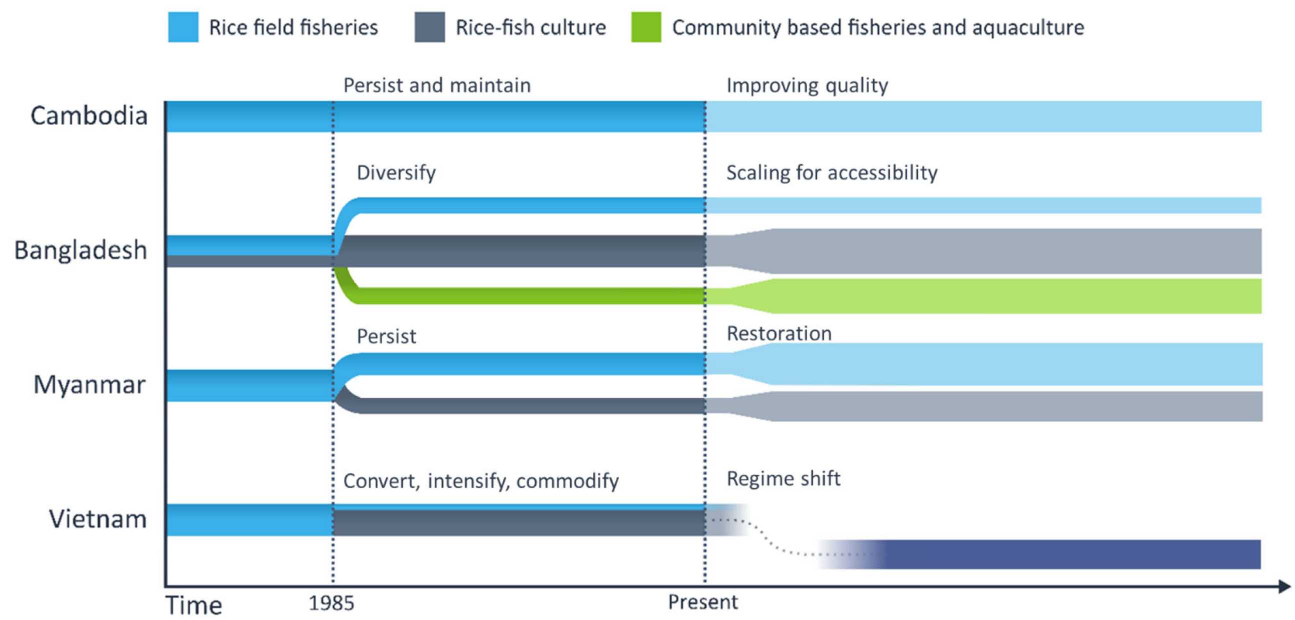

FIGURE 2 | Transformation pathways for rice-fish production practices. Starting from similar initial practices (predominantly rice field fisheries), rice-fish production in the four case study countries transitioned or transformed along different pathways according to their context and the objectives that followed from the Green Revolution (ca. 1985) onwards. During the present opportunity for food systems transformations, four potential pathways are foreseen, once again depending on the context and objectives in the push for sustainable food systems.

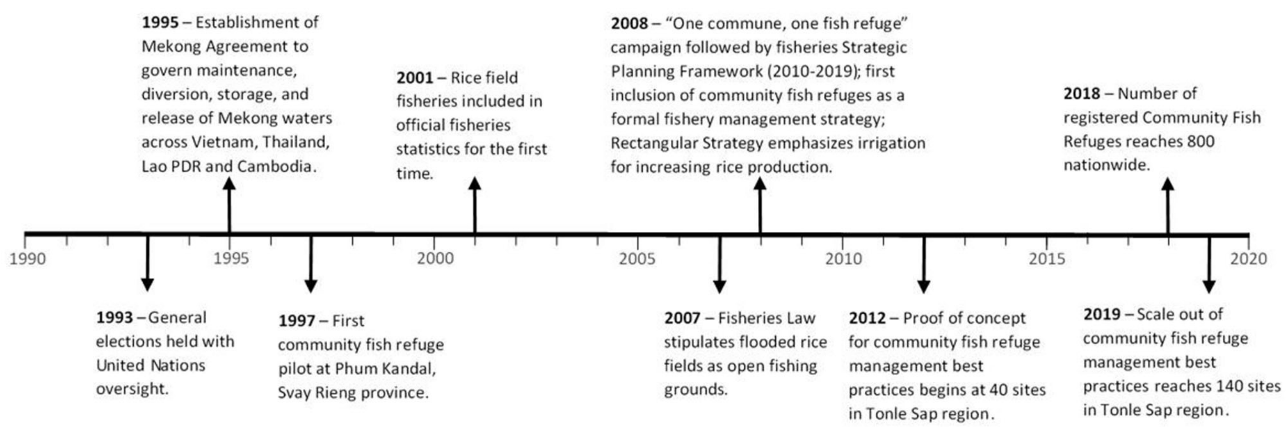

FIGURE 3 | Timeline of events that influenced rice-fish production practices in Cambodia.

concentration of poverty in rural areas, pronounced rural migration (Ingalls et al., 2018), and low Gross National Income per capita ($1,063, the lowest among the four case study countries; The World Bank, 2017b). Another challenge is to improve nutritional outcomes. Despite relatively high availability of freshwater fish per capita (**Supplementary Table 2**; FAO, 2020a), Cambodia performs poorly in terms of childhood stunting (ranked third among case study countries; GHI, 2019) and prevalence of maternal anemia (ranked fourth among case study countries; WHO, 2016). Potential impediments to achieving nutritional benefits from the relatively high fish consumption rate include demographic or geographical pockets of low fish consumption (for example, low fish consumption in children under 2 years of age) and issues of food safety, sanitation infrastructure, and lack of available clean water (Kawarazuka and Béné, 2011; Vyas et al., 2016). A transformation focused on availability of affordable fish for consumption and production of high-quality rice and fish for income generation could address these nutritional and livelihood challenges. Production of high-value rice and fish and ensuring their quality along the value chain could also improve international trade in the face of the large volumes of cheap rice and fish produced in

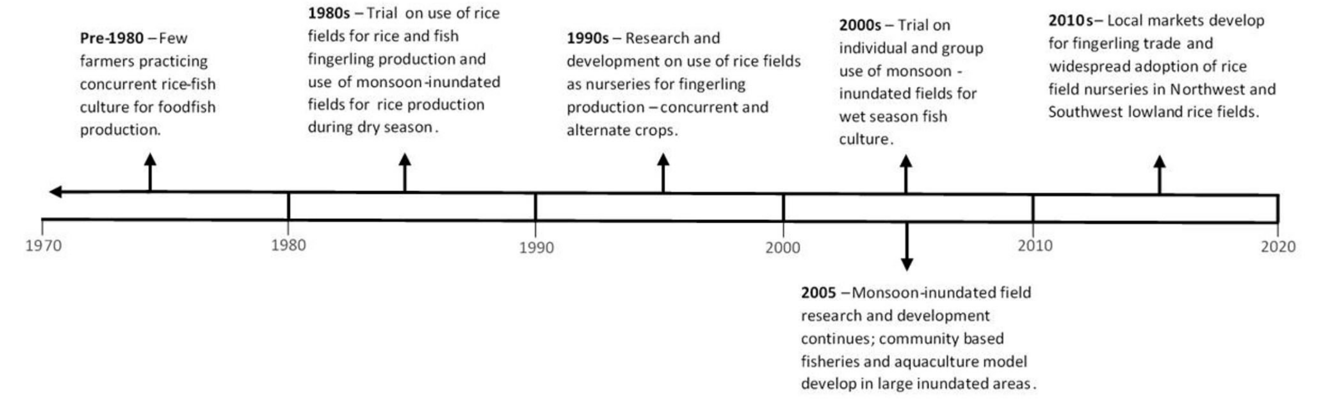

FIGURE 4 | Timeline of events that influenced emerging rice-fish production practices in Bangladesh.

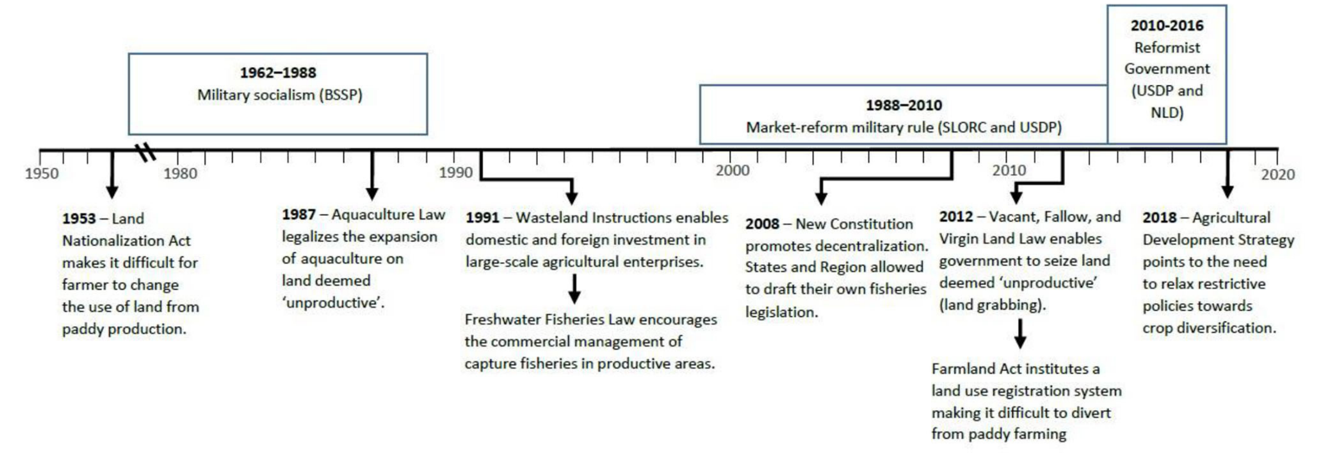

FIGURE 5 | Timeline of events that influenced and ultimately restricted rice-fish production practices in Myanmar.

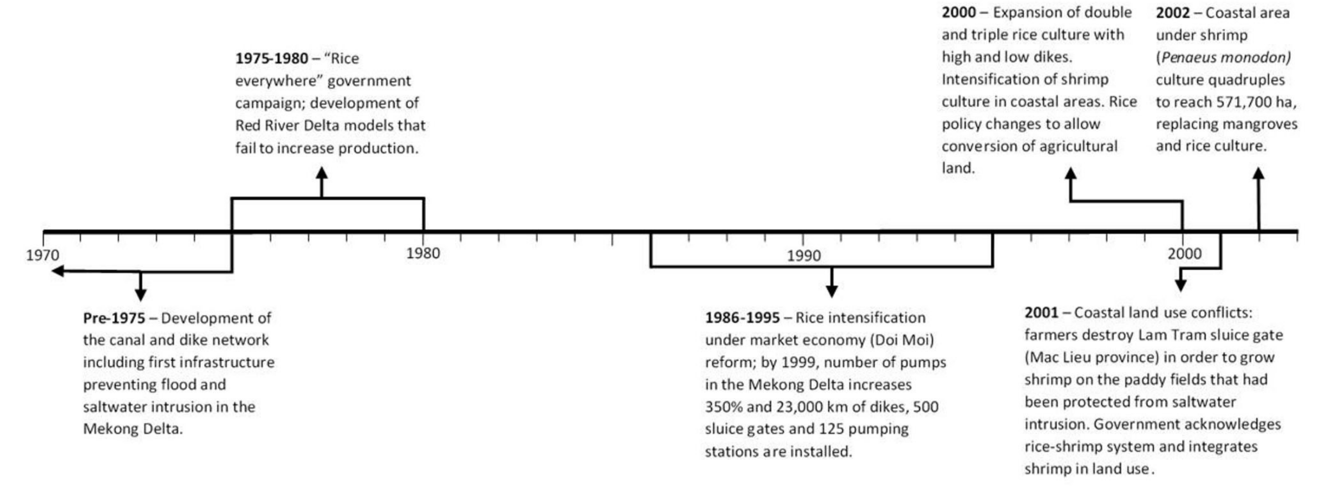

FIGURE 6 | Timeline of events that influenced rice-fish production practices in Vietnam's Mekong Delta.

nearby countries. Quality assurance would most likely require substantial investments, properly targeted incentives for value chain development, and improvements in regulatory policies and their implementation (Ponte et al., 2014).

Water demand is a growing challenge due to recurrent dry periods and increased frequency and/or severity of adverse conditions during rice cultivation (Chhinh et al., 2014; Thangrak et al., 2020), the limited capacity of existing reservoirs in the Tonle Sap basin (Johnston et al., 2014), "water-scavenging" irrigation at farm level (Mukherji et al., 2009), and large scale upstream hydropower development affecting the Mekong and its inflow into the Tonle Sap (Arias et al., 2014). This last factor has already been linked to an expected decline in food and nutrition security through loss of fish availability (Golden et al., 2019). Local mitigation measures such as effective water management, "fish friendly" designs for irrigation development (McCartney et al., 2019), and continued community fish refuge support and scaling of best management practices (Kim et al., 2019) are essential for sustaining rice field fisheries. Some policies have recognized the benefits of rice field fisheries and supported innovations to enhance performance. However, more policy consistency is needed to ensure irrigation and agricultural intensification are not carried out at the expense of natural water flow and biodiversity, for example the directive on irrigation development (MAFF, 2017) and the promotion of rice dry season crop intensification in the Tonle Sap region (RGC, 2008).

Bangladesh

Integrated rice and fish production practices diversified during the Green Revolution in Bangladesh due to aims of livelihood diversification alongside irrigation development for food system transformation. Diversification pursued due to famine, very low income per capita (the second lowest among all nations in 1975; World Bank Group, 2015), high levels of landlessness, and very small farm size. Bangladesh's economy also diversified away from agriculture (World Bank Group, 2015). However, rice and fish remain important agricultural products and dietary staples. Fisheries, and aquaculture in particular, may be considered key sectors for livelihood diversification and food and nutrition security, especially in rural areas. Around 11% of Bangladesh's population is employed in fisheries full or part-time (DoF, 2018). Aquaculture in particular provides rural income opportunities for landholders and landless alike (Belton et al., 2014). Improved fishery and aquaculture production remains a policy objective of Bangladesh for enhancing both employment and income, and food and nutrition security. Fisheries and aquaculture remain important contributors to agricultural gross domestic product and recently became productive enough to consider the nation's fish supply as self-sufficient (DoF, 2018).

Rice field fisheries in Bangladesh were once widespread, but diminished as dry season fish habitat was lost to intensification of dry season rice cultivation (Dey et al., 2013). Rice-fish culture is prevalent in southern Bangladesh, supporting the livelihoods of an estimated 600,000 people, including farmers, fish traders, and processors (Karim et al., 2014). Referred to in Bangla language as a "*gher*" farming system, rice-fish culture in this region consists primarily of alternating culture and most commonly incorporates shrimp and prawn, selected for their export value and high income potential for producers (Rahman et al., 2006; Belton, 2016; Faruque et al., 2017). The widespread production of shrimp and prawn has led to the development of hatcheries and irrigation infrastructure, adoption of compatible rice varieties, and more employment opportunities.

Two additional RFPPs, rice field nurseries and community based fisheries and aquaculture (covering approximately 3,000 and 50,000 hectares, respectively), are emerging through innovations responding to investment, climatic, demographic and/or economic changes (**Figure 4**). The rice field nursery model emerged in the 1980s and 1990s, when farmers opted to pilot fingerling production that required less investment than fish grow-out and was more amenable to the rice production cycle, using lower water depths and shorter growing periods (Barman and Little, 2006). Increased demand for fingerlings, availability of inputs including fry and commercial feed, and the relatively low risk and quick return on investment also encouraged farmer adoption of rice field nurseries. Currently, little information is published on the environmental, food security, and income benefits of these nurseries.

Community based fisheries and aquaculture emerged largely in Bangladesh's northwest (e.g., Rajshahi district) and central regions (e.g., Cumilla district; Toufique and Gregory, 2008; Dey et al., 2013). Innovation of the management model was essential for this RFPP's success. A community based committee is formed from diverse stakeholders, receives training, and develops functional rules and regulations with support from formal institutions such as local government, Department of Fisheries, non-governmental organizations, and members of civil society (Joffre and Sheriff, 2011). Governance is challenging, especially to ensure inclusion of fishers and landless individuals and equity of benefit sharing (e.g., Toufique and Gregory, 2008). When managed inclusively, employment opportunities are generated and fishers gain additional fishing opportunity for up to 6 months each year (Haque and Dey, 2017). Successful examples have demonstrated that community based fisheries and aquaculture increased expenditure equality by 15% among community participants (Haque and Dey, 2016). In addition, the increased fish production bolstered fish consumption, especially for landless non-fishers (33% increase in annual per capita fish consumption) and improved household incomes from fish by a factor of 3.7 (Haque and Dey, 2017).

Adequate nutrition remains a challenge in Bangladesh, particularly in terms of hunger and maternal anemia (ranked fourth and third among the four case study countries, respectively; WHO, 2016; GHI, 2019). Natural disasters and climate change effects are also key challenges, with diverse patterns affecting food production across the country (Dastagir, 2015; Raihan et al., 2020). Scaling of RFPPs with an emphasis on resilience to climate change and accessibility for local consumption could ensure the contribution of rice and fish production to improved nutrition. Community based fisheries and aquaculture is a suitable candidate for scaling, considering the demonstrated positive benefits for household consumption. Effective scaling will require development of policy conducive to RFPPs and producer-focused initiatives such as dissemination of farm management best practices, market development for inputs and outputs of fish culture, as well as initiatives to support the entire value chain (e.g., transportation facilities and financial and information technology instruments).

Myanmar

Rice production has remained the primary focus of agricultural and food policy in Myanmar since the Green Revolution, despite delivering relatively low yields and economic returns per unit of land area (Ministry of Agriculture, Livestock and Irrigation, 2018; World Bank, 2018). Rice and fish are the fourth largest contributors to gross domestic product and are the main sources of rural incomes (Raitzer et al., 2015; FAO, 2020b). The government has declared revitalization of the agriculture sector as a priority, following the impacts of a tumultuous political history (**Figure 5**).

Rice field fisheries have continued as an abundant but "hidden harvest" in Myanmar. Myanmar's 2012 Farmland Act has reinforced the stringent conditions required for the conversion of rice fields for any other permanent purpose (Gregory, 2017), constraining physical modifications to the rice farming landscape for fisheries enhancement or integration of aquaculture. Nevertheless, informal rice field fisheries are very common (Gregory, 2017; Oo and Mackay, 2018). While not officially recognized, rice field fisheries remain important for food and nutrition security in rice farming regions and may in fact constitute a large proportion of inland fisheries production in Myanmar. A survey of 180 leasable fishing lots in the Ayeyarwady Region found that 34% of these lots included seasonally flooded wetlands that were used for rice cultivation during the dry season. Fish productivity in these areas was comparable to the most productive seasonal floodplains in Bangladesh and Cambodia (Tezzo et al., 2018). Most households participating in rice field fisheries benefitted from savings due to self-supply of fish and income from selling surplus catch (Gregory, 2017). Fishery decline is observed, however, likely due to large numbers of fishers, increasing use of agrochemicals, and electrofishing (Gregory, 2017). Rice-fish culture is also present in Myanmar, but much less prominent. Shrimp are produced in saline zones through alternating rice-fish culture, but very little rice-fish culture occurs in fresh and brackish water areas (Gregory, 2017). The number of farmers practicing concurrent rice-fish culture in freshwater regions is currently limited due to restrictions in the 2012 Farmland Act.

Myanmar is showing signs of shifting from a monoculture focus to diversified production. Recent on-farm piloting of concurrent rice-fish culture showed positive benefits for rice yield, agrochemical reduction, and mean gross margin (which was 25% greater than that of rice monoculture; Dubois et al., 2019). These results highlight the improved resource efficiency and potential economic benefits of adopting concurrent rice-fish culture in the Ayeyarwady Delta without compromising rice production. Approximately 70% of the fish produced in the research trials was sold to the local market and purchased by rural and peri-urban consumers, while 30% was consumed by the farming households (Dubois et al., 2019), indicating the potential to improve the diets of rice farming households and contribute to food and nutrition security in the region.

Economic inequality and food insecurity remain important challenges. Myanmar has the highest income inequality among the four case study countries (19.9% as of 2018; UNDP, 2020). Hunger and malnutrition affect large segments of the population and food insecurity remains a serious problem among resource poor people (Robertson et al., 2018). Inequalities in fish consumption exist, with the poorest households consuming less than one-quarter of the amount consumed by wealthier households (Wilson and Wai, 2013). In terms of environmental challenges, the central dry zone of Myanmar faces water availability limitations (Boori et al., 2017), while coastal regions face saline intrusion along with sea level rise (Oo et al., 2018).

Further studies are needed to assess the extent and benefits of RFPPs in Myanmar. Rice field fisheries likely make substantial contributions to food and nutrition security. Concurrent rice-fish culture could maintain rice production relative to rice monoculture, with the added benefit of fish as a more nutritious food and higher value commodity, however this has yet to be tested at scale (Dubois et al., 2019). Monoculture-focused policy and practices have limited the extent of RFPPs and land use regulations limit widespread adoption of rice-fish culture. The fast modernization of the agriculture sector may constitute another significant barrier to RFPPs. Further research on the current status and benefits of RFPPs to women and men in farming and non-farming households could provide guidance for policy makers to facilitate adoption and/or restoration of RFPPs toward local incomes and food and nutrition security.

Vietnam

Transformation of fish and rice sectors have been pronounced since the Green Revolution in Vietnam. The improvement in rice yields and production secured self-sufficiency and exportation, and the Mekong delta remains the "rice bowl" of the country, producing 50% of Vietnam's paddy rice (25 million tons) and 90% of its rice exports (Demont and Rustaert, 2017; Thang, 2017). The once prolific rice field fisheries of Vietnam's Mekong delta declined in tandem with rice intensification. Although the delta once produced up to 90% of total inland fisheries production in southern Vietnam (Taki, 1975), rural households in the delta have experienced significant decreases in wild fish catch and consumption (Berg et al., 2017; Nguyen et al., 2018).

Environmental and infrastructure changes have been profound as well. The Mekong Delta now hosts over 10,000 km of canals and 20,000 km of dykes, and irrigation infrastructure encompasses 90% of its cropland (Nguyen et al., 2020). Saline water intrusion is increasing in the delta due to land subsidence (to which groundwater extraction for irrigation is a contributing factor; Minderhoud et al., 2017), sea level rise, high levels of downstream sand mining, and reduced upstream flow of water and sediment (largely due to hydropower infrastructure along the Mekong and its tributaries; Eslami et al., 2019). Variability in soil fertility and large areas of acid sulfate soil further constrain the intensification of rice culture in the delta (Husson et al., 2000).

Policy mandates and market incentives have operated to convert and intensify RFPPs in the Mekong Delta. Intensification and commodification of fish (including prawn and shrimp) production followed the initial Green Revolution push for rice production and commodification (**Figure 6**). In response to the low farm-gate prices for the high-yield but low quality rice (Demont and Rustaert, 2017) and increased use of inputs that keep farmer incomes low (Berg et al., 2017), farmers have diversified production in increasing numbers since the early 2000s. The high value and salt tolerance of shrimp motivated farmers to convert a large area planned for rice intensification to shrimp aquaculture and alternating rice-shrimp culture (Hoanh et al., 2003).

Extensive alternating rice-shrimp culture now covers 160,000 hectares (Hai et al., 2016), or about 5% of the wet season rice cultivation area of Vietnam (General Statistics Office, 2016). Freshwater finfish aquaculture has also increased in the delta (Nguyen et al., 2020), as have alternating culture of freshwater prawn and rice (Nguyen et al., 2020) and concurrent culture of rice- freshwater prawn followed by shrimp (*Penaeus vannamei* or *Penaeus monodon*) is also increasing in the coastal zone of the Mekong Delta (Hai et al., 2017). Net returns of alternating rice-shrimp culture can be as high as $3,000 per hectare annually (AMDI, 2016). When compared with rice monoculture, rice-shrimp culture can improve economic and social equity and provide significantly higher net income at the household level, but may be difficult for poorer households to implement because of the high initial investment and reliance on household labor (Grassi et al., 2017). Although the shrimp sector is known for "boom and bust" cycles, alternating rice-shrimp culture in Vietnam appears to be more stable, at least in part because it is less prone to disease outbreaks than intensive aquaculture (Joffre and Bosma, 2009; Duc et al., 2015). While the rice may be consumed locally, nationally, or internationally, the shrimp are exported and rarely consumed locally, limiting the direct contribution to food and nutrition (Vu, 2012). Nonetheless, of the four countries we examine here, Vietnam has the lowest rates of childhood stunting and maternal anemia (WHO, 2016; GHI, 2019), due in part to increases in animal source food consumption in recent decades (Stür and Gray, 2015).

Currently, climate change, freshwater availability, and water quality are the greatest challenges for Vietnam's rice and fish sectors. Semi-intensive rice-shrimp culture can release exotic species, nutrient loads, and anti-biotic and agrochemical residues, even though rice-shrimp producers tend to report lower application of pesticides and antibiotics than in intensive shrimp culture (Be et al., 1999; Binh et al., 2018; Braun et al., 2019). Promotion of rice-shrimp management practices that limit nutrient discharge and restore connectivity between the plot and the wider ecosystem (e.g., Joffre et al., 2018) could mitigate some of the environmental and health concerns of high-input practices.

Recent severe drought and increasing saline intrusion is causing crop loss, particularly for rice (South China Morning Post, 2020). Alternating rice-shrimp culture may expand in the delta as saltwater intrusion continues, but it may be replaced by shrimp monoculture in areas where the duration of saline intrusion increases. The Ministry of Agriculture and Rural Development plans to develop the rice-shrimp area in the Mekong Delta to 250,000 hectares producing 125,000–150,000 metric tons by 2030, rendering a value of up to $1.3 billion and providing stable jobs for over 1 million people in rural areas (AMDI, 2016). At the same time, if there are no adaptation efforts, profit from intensive and semi-intensive shrimp farming is estimated to fall by $41 per hectare by 2050 due to climate change (affected in particular by increasing temperatures and lack of fresh water; Kam et al., 2012). Rising temperatures are anticipated to not only adversely affect shrimp, but also rice yields (Nhan et al., 2011). Although expansion of other RFPPs could further contribute to food system sustainability, continuing salinization and subsidence of the delta may require more dramatic shifts or a conversion to alternative production practices.

DISCUSSION

Food and nutrition security challenges are intensifying in the face of increasing demand for food as well as climate change and associated water stress and environmental degradation (Hanjra and Qureshi, 2010; Myers et al., 2017). In its current form, agriculture is overreaching the limits of global environmental sustainability (Gordon et al., 2017; Gerten et al., 2020). The typology and case studies in this review demonstrate how long-standing, adapting, and emergent agroecological practices can contribute to addressing these challenges in rice and fish producing nations. Reflecting on the Green Revolution approach to transforming food systems, the typology and case studies illustrate five shifts in approach, set out below, that could nudge food systems toward greater sustainability and better nutritional outcomes.

The first shift toward sustainable and nutrition-sensitive food systems is to apply an agroecological lens when identifying the range of production practices that can be enabled, improved, and scaled. The Green Revolution primarily promoted high-input practices and in doing so, sidelined other practices that are evidenced to effectively manage water availability, soil fertility, and pest control (Tilman, 1998; Tilman et al., 2002). The RFPP typology we developed illustrates the range and diversity of available agricultural practices for rice and fish production, including nutrition-sensitive practices. This typology broadens the solution space under consideration and illustrates opportunities for new practices or strengthening of agroecological features associated with existing practices.

The second shift in the approach to food system transformations is to account for the diversity of food system objectives. The Green Revolution focused primarily on the objective of increasing quantities of staple crops (Hazell, 2009; Pingali, 2012). Our review illustrates that, alongside this production goal, national food systems were also attuned to other objectives: nutrition gains and biodiversity conservation in Cambodia; livelihood diversification in Bangladesh;

self-sufficiency in Myanmar; export value in Vietnam; and improving rural incomes in all cases. The contemporary demands for more sustainable and nutrition-sensitive food systems explicitly prioritize a much broader suite of objectives than the Green Revolution (De Schutter, 2017) and present an opportunity to build upon the breadth of food systems objectives found in the national food systems of Cambodia, Bangladesh, Myanmar, and Vietnam. The degree to which each objective will continue to be prioritized depends on the influence of divergent views of what constitutes a sustainable food system (Béné et al., 2019) and potential transformation pathways (Bezner Kerr, 2012; Blythe et al., 2018) within investments and policy.

The third shift is to align decision-making and planning tools with the broader range of recognized objectives, particularly through adjustments of metrics and evaluation frameworks. Food systems decisions during the Green Revolution were evaluated against indicators and targets relating to production, yield, Gross Domestic Product, and (in some cases) employment (IPES-Food, 2016; De Schutter, 2017). As public and private actors increase commitments toward sustainable food systems (Asian Development Bank, 2015; McCartney et al., 2019), evaluation metrics must align with, and ensure accountability to, a broader set of nutrition, equity, and environmental targets. In addition to evaluating food system performance, a shift in approach to metrics can improve tracking of feedback loops among food system components and outcomes and can facilitate course-checking and course-correction. Existing measures must also be refined to better distinguish among production practices, especially to better account for fisheries and diverse aquatic foods (Thilsted et al., 2016; Funge-Smith and Bennett, 2019). For example, in rice and fish producing nations, rice monoculture and aquaculture areas are often well-represented in national statistics, but areas of integrated and agroecological production such as rice field fisheries remain largely unrepresented or misrepresented as rice monoculture.

The fourth shift brings equity to the fore through contextualized and inclusive approaches to research and innovation. The Green Revolution has been criticized for relying on generic technologies and innovations that are disseminated globally with too little consideration for social, ecological, and agricultural context and diversity (Horlings and Marsden, 2011). Transformations devoid of agroecological practices are prone to excluding and marginalizing certain stakeholders, most notably vulnerable rural farming households (Bezner Kerr, 2012), and can enhance social and environmental inequalities (Bezner Kerr, 2012; Blythe et al., 2018). An emerging paradigm shift in agronomy emphasizes support for local innovation to develop emergent and adaptive solutions that suit the heterogeneity of farmer-fisher contexts and objectives (Sinclair and Coe, 2019). Ensuring the alignment of innovations, institutions, and policies is also necessary for effective transformation (Horlings and Marsden, 2011; Bezner Kerr, 2012; Joffre et al., 2018). The suite of production practices represented in the RFPP typology allow for continued testing and refining of innovations to further improve nutrition, equity, and environmental outcomes. The innovations emerging from RFPPs demonstrate gains or promise in enhancing management of landscape connectivity (in the Mekong Delta; Joffre et al., 2018; Nguyen et al., 2020), equity and inclusivity (in Bangladesh; Haque and Dey, 2016), and enabling adaptation in the face of changing environmental and sociopolitical conditions (in Myanmar; Dubois et al., 2019). Even for the long-standing rice field fisheries in Cambodia, innovation and research have enabled adaptation to the contemporary agricultural, ecological, and institutional context (Kim et al., 2019).

To support this contextualized and inclusive approach to research and innovation, research must more consistently investigate food and nutrition provision, equitable benefit sharing, and environmental outcomes of different production practices. These shifts in research focus will help meet Blesh et al. (2019) call for "*place-based, adaptive, and participatory solutions that simultaneously attend to local institutional capacities, agroecosystem diversification and ecological management, and the quality of local diets*." For example, rice field fisheries outcomes can vary due to environmental conditions (both natural biophysical characteristics and managed attributes such as barriers to water flow and migration) and fishing practices, including access to fishing grounds (Freed et al., 2020), and also differ from outcomes of other RFPPs. Understanding the range of outcomes produced under variable contexts and among practices would help guide decision-making on whether to invest in enhancing a rice field fishery, an alternative RFPP, or another farming approach. Research is also needed on actors and practices along the rest of the value chain, institutions, and policies, to determine their influence on food systems equity and sustainability (Ericksen et al., 2010; Horlings and Marsden, 2011; De Schutter, 2017).

Finally, the fifth shift in the approach to food systems transformations is to build adaptive capacity to cope with evolving challenges and harness opportunities that arise during the implementation period. Substantial environmental change is occurring across South and Southeast Asia, e.g., salinization in the deltas in Vietnam, Myanmar, and Bangladesh (Dastagir, 2015; Minderhoud et al., 2017; Oo et al., 2018; Eslami et al., 2019); increasing frequency and severity of already disastrous extreme weather events in Bangladesh (Dastagir, 2015; Raihan et al., 2020); and water scarcity in parts of Myanmar and Cambodia (Chhinh et al., 2014; Boori et al., 2017; Thangrak et al., 2020). RFPPs can help maintain adaptive capacity in the face of environmental change, especially in coastal Bangladesh and Vietnam (Hai et al., 2016; Faruque et al., 2017). This adaptability is a unique feature of diversified agroecological production practices, in contrast to the "lock-in" effect observed in monoculture systems (Chhetri et al., 2010; De Schutter, 2017; Magrini et al., 2018). A lock-in, or the "*cumulative outcome of technological trajectories adopted by farmers and promoted by extension services, agricultural policies, and agricultural research systems*" (Chhetri et al., 2010), requires concerted efforts across institutions, disciplines, and scales to break (Chhetri et al., 2010; Meynard et al., 2018).

CONCLUSION

Systems perspectives to the concurrent environmental and food and nutrition security challenges we now face are gaining traction in policy arenas, providing an opportunity to embrace diversity in visions of agricultural change. Enabling the contribution of agroecological approaches to transforming food systems has the potential to improve progress toward the "Zero Hunger" Sustainable Development Goal (SDG). The evidence we synthesize demonstrates this for rice and fish producing regions. Integrated and agroecological rice-fish production practices can contribute to productivity and income for small-scale food producers and to ecosystem maintenance and capacity for adaptation to climate change and natural disasters, in alignment with SDG targets 2.3 and 2.4. Implementation of the five shifts we propose for food system transformations could maintain or further improve sufficient rice yields and production of rice and fish. Beyond that, these shifts support ecological integrity and biodiversity conservation alongside the provision of a broad range of nutrition and livelihood benefits, commensurate with a holistic vision of sustainable food systems.

AUTHOR CONTRIBUTIONS

SF, YK, and PC contributed to conceptualization and methodology. SF conducted formal analysis. All authors contributed to writing and editing.

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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.2020.576179/full#supplementary-material

REFERENCES

AFD and CIRAD (2018). *Supporting the Agro-Ecological Transition in the Global South*. Paris.

Ahmed, M., and Lorica, M. H. (2002). Improving developing country food security through aquaculture development - lessons from Asia. *Food Policy* 27, 125–141. doi: 10.1016/S0306-9192(02)00007-6

Ahmed, N., Zander, K. K., and Garnett, S. T. (2011). Socioeconomic aspects of rice-fish farming in Bangladesh: opportunities, challenges and production efficiency. *Aust. J. Agric. Resour. Econ.* 55, 199–219. doi: 10.1111/j.1467-8489.2011.00535.x

Ali, A. B. (1990). Some ecological aspects of fish populations in tropical ricefields. *Hydrobiologia* 190, 215–222. doi: 10.1007/BF00008188

Altieri, M. A. (2002). Agroecology: the science of natural resource management for poor farmers in marginal environments. *Agric. Ecosyst. Environ.* 93, 1–24. doi: 10.1016/S0167-8809(02)00085-3

AMDI (2016). *Development of Rice-Shrimp Farming in the Mekong River*. Vietnam.

Amilhat, E., Lorenzen, K., Morales, E. J., Yakupitiyage, A., and Little, D. C. (2009). Fisheries production in Southeast Asian farmer managed aquatic systems (FMAS) I. Characterisation of systems. *Aquaculture* 296, 219–226. doi: 10.1016/j.aquaculture.2009.08.014

Arias, M. E., Cochrane, T. A., and Elliott, V. (2014). Modelling future changes of habitat and fauna in the tonle sap wetland of the mekong. *Environ. Conserv.* 41, 165–175. doi: 10.1017/S0376892913000283

Arthur, R. I., and Friend, R. M. (2011). Inland capture fisheries in the mekong and their place and potential within food-led regional development. *Glob. Environ. Chang.* 21, 219–226. doi: 10.1016/j.gloenvcha.2010.07.014

Asian Development Bank (2015). *Operational Plan for Agriculture and Natural Resources: Promoting Sustainable Food Security in Asia and the Pacific in 2015-2020*. Mandaluyong City: Asian Development Bank.

Barman, B. K., and Little, D. C. (2006). Nile tilapia (*Oreochromis niloticus*) seed production in irrigated rice-fields in Northwest Bangladesh—an approach appropriate for poorer farmers? *Aquaculture* 261, 72–79. doi: 10.1016/j.aquaculture.2006.06.018

Bartley, D. M., De Graaf, G. J., Valbo-Jørgensen, J., and Marmulla, G. (2015). Inland capture fisheries: status and data issues. *Fish. Manag. Ecol.* 22, 71–77. doi: 10.1111/fme.12104

Baumgartner, L., Marsden, T., Millar, J., Thorncraft, G., Phonekhampheng, O., Homsombath, K., et al. (2016). *Development of Fish Passage Technology to Increase Fisheries Production on Floodplains in the Lower Mekong Basin*. Final Report, Project FIS/2009/041. Camberra, ACT: ACIAR, 75.

Be, T., Dung, L., and Brennan, D. (1999). Environmental costs of shrimp culture in the rice-growing regions of the Mekong Delta. *Aquac. Econ. Manag.* 3, 31–42. doi: 10.1080/13657309909380231

Belton, B. (2016). Shrimp, prawn and the political economy of social wellbeing in rural Bangladesh. *J. Rural Stud.* 45, 230–242. doi: 10.1016/j.jrurstud.2016.03.014

Belton, B., Ahmed, N., and Murshed-e-Jahan, K. (2014). *Aquaculture, Employment, Poverty, Food Security and Well-Being in Bangladesh: A Comparative Study*. Penang: CGIAR Research Program on Aquatic Agricultural Systems. Program Report: AAS-2014-39.

Béné, C., Barange, M., Subasinghe, R., Pinstrup-Andersen, P., Merino, G., Hemre, G. I., et al. (2015). Feeding 9 billion by 2050 – putting fish back on the menu. *Food Secur.* 7, 261–274. doi: 10.1007/s12571-015-0427-z

Béné, C., Oosterveer, P., Lamotte, L., Brouwer, I. D., de Haan, S., Prager, S. D., et al. (2019). When food systems meet sustainability – current narratives and implications for actions. *World Dev.* 113, 116–130. doi: 10.1016/j.worlddev.2018.08.011

Berg, H., Ekman Söderholm, A., Söderström, A. S., and Tam, N. T. (2017). Recognizing wetland ecosystem services for sustainable rice farming in the Mekong Delta, Vietnam. *Sustain. Sci.* 12, 137–154. doi: 10.1007/s11625-016-0409-x

Bezner Kerr, R. (2012). Lessons from the old green revolution for the new: social, environmental and nutritional issues for agricultural change in Africa. *Prog. Dev. Stud.* 12, 213–229. doi: 10.1177/146499341101200308

Binh, V., Dang, N., Anh, N., Ky, L., and Thai, P. (2018). Antibiotics in the aquatic environment of Vietnam: sources, concentrations, risk and control strategy. *Chemosphere* 197, 438–450. doi: 10.1016/j.chemosphere.2018.01.061

Blesh, J., Hoey, L., Jones, A. D., Friedmann, H., and Perfecto, I. (2019). Development pathways toward "zero hunger." *World Dev.* 118, 1–14. doi: 10.1016/j.worlddev.2019.02.004

Blesh, J., and Wolf, S. A. (2014). Transitions to agroecological farming systems in the mississippi river basin: toward an integrated socioecological analysis. *Agric. Hum. Values* 31, 621–635. doi: 10.1007/s10460-014-9517-3

Blythe, J., Silver, J., Evans, L., Armitage, D., Bennett, N. J., Moore, M. L., et al. (2018). The dark side of transformation: latent risks in contemporary sustainability discourse. *Antipode* 50, 1206–1223. doi: 10.1111/anti.12405

Boori, M. S., Choudhary, K., Evers, M., and Paringer, R. (2017). A review of food security and flood risk dynamics in central dry zone area of Myanmar. *Procedia Eng.* 201, 231–238. doi: 10.1016/j.proeng.2017.09.600

Braun, G., Braun, M., Kruse, J., Amelung, W., Renaud, F. G., Khoi, C. M., et al. (2019). Pesticides and antibiotics in permanent rice, alternating rice-shrimp and permanent shrimp systems of the coastal Mekong Delta, Vietnam. *Environ. Int.* 127, 442–451. doi: 10.1016/j.envint.2019.03.038

CARD, and TWG-SP&FS (2014). *National Strategy for Food Security and Nutrition 2014-2018*. Phnom Penh: Council for Agricultural and Rural Development and Technical Working Group for Social Protection and Food Security and Nutrition.

Caron, P., Ferrero y de Loma-Osorio, G., Nabarro, D., Hainzelin, E., Guillou, M., Andersen, I., et al. (2018). Food systems for sustainable development: proposals for a profound four-part transformation. *Agron. Sustain. Dev.* 38:41. doi: 10.1007/s13593-018-0519-1

Chan, C., Tran, N., Dao, C., Sulser, T., Phillips, M., Batka, M., et al. (2017). *Fish to 2050 in the ASEAN Region*. Washington, DC.

Cheng-Fang, L., Cou-Gui, C., Jin-Ping, W., Ming, Z., Wei-Ling, Y., and Ahmad, S. (2008). Nitrogen losses from integrated rice-duck and rice-fish ecosystems in southern China. *Plant Soil* 307, 207–217. doi: 10.1007/s11104-008-9597-1

Chheng, P., Un, S., Tress, J., Simpson, V., and Sieu, C. (2016). *Fish Productivity by Aquatic Habitat and Estimated Fish Production in Cambodia*. Phnom Penh.

Chhetri, N. B., Easterling, W. E., Terando, A., and Mearns, L. (2010). Modeling path dependence in agricultural adaptation to climate variability and change. *Ann. Assoc. Am. Geogr.* 100, 894–907. doi: 10.1080/00045608.2010.500547

Chhinh, N., Cheb, H., and Heng, N. (2014). Drought risk in Cambodia: assessing costs and a potential solution. *Asian J. Agric. Dev.* 11, 1–16. doi: 10.22004/ag.econ.202425

Coates, D. (2002). *Inland Capture Fishery Statistics of Southeast Asia: Current Status and Information Needs*. Bangkok.

Coche, A. G. (1967). Fish culture in rice fields a world-wide synthesis. *Hydrobiologia* 30, 1–44. doi: 10.1007/BF00135009

Cooke, S. J., Allison, E. H., Beard, T. D., Arlinghaus, R., Arthington, A. H., Bartley, D. M., et al. (2016). On the sustainability of inland fisheries: finding a future for the forgotten. *Ambio* 45, 753–764. doi: 10.1007/s13280-016-0787-4

Costa-Pierce, B. A. (1992). "Rice-fish systems as intensive nurseries," in *Rice-Fish Research and Development in Asia. ICLARM Conference Proceedings*, eds C. R. dela Cruz, C. Lightfoot, B. A. Costa-Pierce, V. R. Carangal, and M. P. Bimbao (Makati city: ICLARM), 117–130.

Cramb, R., and Newby, J. (2015). "Trajectories of rice-farming households in mainland Southeast Asia," in *Trajectories of Rice-Based Farming Systems in Mainland Southeast Asia*, ed R. Cramb (Canberra, ACT: Australian Centre for International Agricultural Research), 35–72.

Dastagir, M. R. (2015). Modeling recent climate change induced extreme events in Bangladesh: a review. *Weather Clim. Extrem.* 7, 49–60. doi: 10.1016/j.wace.2014.10.003

De Schutter, O. (2017). The political economy of food systems reform. *Eur. Rev. Agric. Econ.* 44, 705–731. doi: 10.1093/erae/jbx009

Demont, M., and Rustaert, P. (2017). Restructuring the Vietnamese rice sector: towards increasing sustainability. *Sustainability* 9:325. doi: 10.3390/su9020325

Dey, M. M., Spielman, D. J., Haque, A. B. M. M., Rahman, M. S., and Valmonte-Santos, R. (2013). Change and diversity in smallholder rice-fish systems: recent evidence and policy lessons from Bangladesh. *Food Policy* 43, 108–117. doi: 10.1016/j.foodpol.2013.08.011

DoF (2018). *Yearbook of Fisheries Statistics of Bangladesh 2017–2018.* Vol. 35, Fisheries Resources Survey System (FRSS), Department of Fisheries. Dhaka: Ministry of Fisheries. p. 129.

Dubois, M. J., Akester, M., Leemans, K., Teoh, S. J., Stuart, A., Thant, A. M., et al. (2019). Integrating fish into irrigation infrastructure projects in Myanmar: rice-fish what if...? *Mar. Freshw. Res.* 70, 1229–1240. doi: 10.1071/MF19182

Duc, P., Thi, T., Hoa, T., Phuong, N., Bosma, R., Hien, V., et al. (2015). Virus diseases risk-factors associated with shrimp farming practices in rice-shrimp and intensive culture systems in Mekong Delta Viet Nam. *Int. J. Sci. Res. Publ.* 5, 1–6.

Dwiyana, E., and Mendoza, T. C. (2006). Comparative productivity, profitability and efficiency of rice monoculture and rice-fish culture systems. *J. Sustain. Agric.* 29, 145–166. doi: 10.1300/J064v29n01_11

Dwiyana, E., and Mendoza, T. C. (2008). Determinants of productivity and profitability of rice-fish farming systems. *Asia Life Sci.* 17, 21–42.

Edwards, P., Zhang, W., Belton, B., and Little, D. C. (2019). Misunderstandings, myths and mantras in aquaculture: its contribution to world food supplies has been systematically over reported. *Mar. Policy* 106:103547. doi: 10.1016/j.marpol.2019.103547

Ericksen, P., Stewart, B., Dixon, J., Barling, D., Loring, P., Anderson, M., et al. (2010). "The value of a food system approach," in *Food Security and Global Environmental Change,* eds J. Ingram and P. Ericksen (London: Earthscan), 25–45.

Eslami, S., Hoekstra, P., Trung, N., Kantoush, S., Van Binh, D., Quang, T., et al. (2019). Tidal amplification and salt intrusion in the Mekong Delta driven by anthropogenic sediment starvation. *Sci. Rep.* 9:18746. doi: 10.1038/s41598-019-55018-9

FAO (2014). *A Regional Rice Strategy for Sustainable Food Security in Asia and the Pacific*. Bangkok.

FAO (2019). *Report of the Special Session on Advancing Integrated Agriculture Aquaculture Through Agroecology, Montpellier, France, 25 August 2018*. Rome.

FAO (2020a). *FAO FishStatJ Database*. Available online at: http://www.fao.org/fishery/statistics/software/FishStatJ/en (accessed October 19, 2020).

FAO (2020b). *FAO in Myanmar*. Available online at: http://www.fao.org/myanmar/fao-in-myanmar/myanmar/en/ (accessed October 19, 2020).

FAO (2020c). *FAOSTAT Database*. Available online at: http://www.fao.org/faostat/en/home (accessed October 19, 2020).

Faruque, G., Sarwer, R. H., Karim, M., Phillips, M., Collis, W. J., Belton, B., et al. (2017). The evolution of aquatic agricultural systems in Southwest Bangladesh in response to salinity and other drivers of change. *Int. J. Agric. Sustain.* 15, 185–207. doi: 10.1080/14735903.2016.1193424

Fernando, C. H. (1993). Rice field ecology and fish culture - an overview. *Hydrobiologia* 259, 91–113. doi: 10.1007/BF00008375

Fisher, B., Naidoo, R., Guernier, J., Johnson, K., Mullins, D., Robinson, D., et al. (2017). Integrating fisheries and agricultural programs for food security. *Agric. Food Secur.* 6, 10–16. doi: 10.1186/s40066-016-0078-0

Fisheries Administration (2011). *Cambodia Strategic Planning Framework for Fisheries 2010-2019*. Phnom Penh.

Fluet-Chouinard, E., Funge-Smith, S., and McIntyre, P. B. (2018). Global hidden harvest of freshwater fish revealed by household surveys. *Proc. Natl. Acad. Sci. U.S. A.* 115, 7623–7628. doi: 10.1073/pnas.1721097115

Freed, S., Kura, Y., Sean, V., Mith, S., Cohen, P., Kim, M., et al. (2020). Rice field fisheries: wild aquatic species diversity, food provision services and contribution to inland fisheries. *Fish. Res.* 229:105615. doi: 10.1016/j.fishres.2020.105615

Frei, M., and Becker, K. (2005). A greenhouse experiment on growth and yield effects in integrated rice–fish culture. *Aquaculture* 244, 119–128. doi: 10.1016/j.aquaculture.2004.11.014

Friend, R. M., Arthur, R. I., and Keskinen, M. (2009) "Songs of the doomed: the continuing neglect of capture fisheries in hydropower development in the Mekong," in *Contested Waterscapes in the Mekong Region: Hydropower, Livelihoods and Governance*, eds F. Molle, T. Foran, and M. Käkönen (London: Earthscan), 307–331. doi: 10.4324/9781849770866

Funge-Smith, S., and Bennett, A. (2019). A fresh look at inland fisheries and their role in food security and livelihoods. *Fish Fish* 20, 1–20. doi: 10.1111/faf.12403

Garaway, C. J., Photitay, C., Roger, K., Khamsivilay, L., and Halwart, M. (2013). Biodiversity and nutrition in rice-based ecosystems; the case of lao PDR. *Hum. Ecol.* 41, 547–562. doi: 10.1007/s10745-013-9602-z

General Statistics Office (2016). *Agriculture, Forestry and Fishing Database*. General Statistics Office of Vietnam. Available online at: https://www.gso.gov.vn/en/agriculture-forestry-and-fishery/ (accessed October 19, 2020).

Gerten, D., Heck, V., Jägermeyr, J., Bodirsky, B. L., Fetzer, I., Jalava, M., et al. (2020). Feeding ten billion people is possible within four terrestrial planetary boundaries. *Nat. Sustain.* 3, 200–208. doi: 10.1038/s41893-019-0465-1 (accessed October 19, 2020).

GHI (2019). *Global Hunger Index*. Available online at: https://www.globalhungerindex.org/results.html (accessed 19 October 2020).

Golden, C. D., Shapero, A., Vaitla, B., Smith, M. R., Myers, S. S., Stebbins, E., et al. (2019). Impacts of mainstream hydropower development on fisheries and human nutrition in the lower mekong. *Front. Sustain. Food Syst.* 3, 1–10. doi: 10.3389/fsufs.2019.00093

Gordon, L. J., Bignet, V., Crona, B., Henriksson, P. J. G., Van Holt, T., Jonell, M., et al. (2017). Rewiring food systems to enhance human health and biosphere stewardship. *Environ. Res. Lett.* 12:100201. doi: 10.1088/1748-9326/aa81dc

Grassi, F., Paris, T. R., and Chi, T. T. N. (2017). *Rice-Rice and Rice-Shrimp Production: A Gender Perspective on Labour, Time Use and Access to Technologies and Services in Southern Vietnam*. Rome: Food and Agriculture Organization of the United Nations.

Gregory, R. (1997). *Ricefield Fisheries Handbook*. Los Banos: International Rice Research Inst.; Phnom Penh: Ministry of Agriculture, Forestry and Fisheries.

Gregory, R. (2017). *Development of Rice Fish Systems (RFS) in the Ayeyarwaddy Delta. Rice Fish Systems Characterisation Study*. Yangon.

Hai, T., Huong, H., Viet, L., Huong, D., and Phuong, N. (2017). Giant freshwater prawn (*Macrobrachium rosenbergii* de Man, 1879) farming in brackish water areas of the Mekong Delta, Vietnam. *Can Tho Univ. J. Sci.* 7, 82–90. doi: 10.22144/ctu.jen.2017.053

Hai, T., Minh, T., Phu, T., and Phuong, N. (2016). "Shrimp industry in Vietnam," in *Progress of Shrimp and Prawn Aquaculture in the World*, eds C. Liao, N. Chao, and E. Leano (Keelung; Manila; Louisiana: National Taiwan Ocean University; The Fisheries Society; World Aquaculture Society), 181–204.

Halwart, M. (1994). *Fish as Biocontrol Agents in Rice: The Potential of Common Carp Cyprinus carpio* (L.) *and Nile Tilapia Oreochromis niloticus* (L.). Weikersheim: Margraf Verlag.

Halwart, M. (1998). Trends in rice-fish farming. *FAO Aquac. Newslett.* 18 (Rome: Food and Agriculture organisation of the United Nations). 3–11.

Halwart, M. (2006). Biodiversity and nutrition in rice-based aquatic ecosystems. *J. Food Compos. Anal.* 19, 747–751. doi: 10.1016/j.jfca.2006.03.012

Halwart, M. (2013). "Valuing aquatic biodiversity in agricultural landscapes," in *Diversifying Food and Diets: Using Agricultural Biodiversity to Improve Nutrition and Health*, eds J. Fanzo, D. Hunter, T. Borelli, and F. *Mattei* (Abingdon: Routledge), 88–108.

Halwart, M., and Gupta, M. (2004). *Culture of Fish in Rice Fields*. Rome: FAO; Penang: WorldFish.

Hanjra, M., and Qureshi, M. (2010). Global water crisis and future food security in an era of climate change. *Food Policy* 35, 365–377. doi: 10.1016/j.foodpol.2010.05.006

Haque, A. B. M. M., and Dey, M. M. (2016). Impact of the community-based fish culture system on expenditure and inequality: evidence from Bangladesh. *J. World Aquac. Soc.* 47, 646–657. doi: 10.1111/jwas.12317

Haque, A. B. M. M., and Dey, M. M. (2017). Impacts of community-based fish culture in seasonal floodplains on income, food security and employment in Bangladesh. *Food Secur.* 9, 25–38. doi: 10.1007/s12571-016-0629-z

Hazell, P. B. R. (2009). *The Asian Green Revolution*. Available online at: https://www.ifpri.org/publication/asian-green-revolution (accessed October 19, 2020).

Heckman, C. W. (1979). *Rice Field Ecology in Northeastern Thailand.* ed J. Illies. Dordrecht: Springer Science+Business Media.

HLPE (2014). *Food Losses and Waste in the Context of Sustainable Food Systems*. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome.

HLPE (2019). *Agroecological and Other Innovative Approaches for Sustainable Agriculture and Food Systems That Enhance Food Security and Nutrition*. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome.

Hoanh, C. T., Tuong, T. P., Gallop, K. M., Gowing, J. W., Kam, S. P., Khiem, N. T., et al. (2003). Livelihood impacts of water policy changes: evidence from a coastal area of the Mekong river delta. *Water Policy* 5, 475–488. doi: 10.2166/wp.2003.0030

Horgan, F. G., Ramal, A. F., Bernal, C. C., Villegas, J. M., Stuart, A. M., and Almazan, M. L. P. (2016). "Applying ecological engineering for sustainable and resilient rice production systems," in *Procedia Food Science*, eds C. N. Walpita, P. Sorgeloos, I. Karunasagar and K. K. D. S. Ranaweera (Belihuloya: Elsevier Srl), 7–15. doi: 10.1016/j.profoo.2016.02.002

Horlings, L. G., and Marsden, T. K. (2011). Towards the real green revolution? Exploring the conceptual dimensions of a new ecological modernisation of agriculture that could "feed the world." *Glob. Environ. Chang.* 21, 441–452. doi: 10.1016/j.gloenvcha.2011.01.004

Hortle, K., Troeung, R., and Lieng, S. (2008). *Yield and Value of the Wild Fishery of Rice Fields in Battambang Province, Near the Tonle Sap Lake*. Vientiane.

Hu, L., Tang, J., Zhang, J., Ren, W., Guo, L., Halwart, M., et al. (2015). Development of rice-fish system: Today and tomorrow. *Chinese J. Eco Agric.* 23, 268–275.

Husson, O., Verburg, P., Phung, M., and Van Mensvoort, M. (2000). Spatial variability of acid sulphate soils in the plain of reeds, Mekong Delta, Vietnam. *Geoderma* 97, 1–19. doi: 10.1016/S0016-7061(00)00016-1

Ingalls, M. L., Diepart, J., Truong, N., Hayward, D., Neil, T., Phomphakdy, C., et al. (2018). *State of Land in the Mekong Region*. Bern; Vientiane: Lao PDR.

IPES-Food (2016). *From Uniformity to Diversity: A Paradigm Shift From Industrial Agriculture to Diversified Agroecological Systems*. Brussels: International Panel of Experts on Sustainable Food Systems. Available online at: https://cgspace.cgiar.org/bitstream/handle/10568/75659/UniformityToDiversity_FullReport.pdf?sequence=1&isAllowed=y (accessed 19 October 2020).

Joffre, O., and Bosma, R. (2009). Typology of shrimp farming in Bac Lieu Province, Mekong Delta, using multivariate statistics. *Agric. Ecosyst. Environ.* 132, 153–159. doi: 10.1016/j.agee.2009.03.010

Joffre, O., Sheriff, N. (2011). *Studies and Reviews 2011-21*. Penang: The WorldFish Center. p. 46.

Joffre, O. M., Klerkx, L., and Khoa, T. N. D. (2018). Aquaculture innovation system analysis of transition to sustainable intensification in shrimp farming. *Agron. Sustain. Dev.* 38:34. doi: 10.1007/s13593-018-0511-9

Johnston, R., da Silva, S., and Try, T. (2014). "Investing in water management to improve productivity of rice-based farming systems in Cambodia," in *A Policy Dialogue on Rice Futures: Rice-Based Farming Systems Research in the Mekong Region.* Proceedings No. 142, ed L. Robins (Phnom Penh: Australian Centre for International Agricultural Research), 116–119.

Johnston, R., Hoanh, C. T., Lacombe, G., Noble, A., Smakhtin, V., Suhardiman, D., et al. (2009). *Scoping Study on Natural Resources and Climate Change in Southeast Asia with a Focus on Agriculture*. Vientiane

Kam, S. P., Badjeck, M-C., Teh, L., Teh, L., and Tran, N. (2012). *Autonomous Adaptation to Climate Change by Shrimp and Catfish Farmers in Vietnam's Mekong River Delta*. Working Paper: 2012-24. Penang: Worldfish.

Karim, M., Sarwer, R., Phillips, M., and Belton, B. (2014). Profitability and adoption of improved shrimp farming technologies in the aquatic agricultural systems of southwestern Bangladesh. *Aquaculture* 428–429, 61–70. doi: 10.1016/j.aquaculture.2014.02.029

Kawarazuka, N., and Béné, C. (2011). The potential role of small fish species in improving micronutrient deficiencies in developing countries: building evidence. *Public Health Nutr.* 14, 1927–1938. doi: 10.1017/S1368980011000814

Kim, M., Mam, K., Sean, V., Brooks, A., Thay, S., Hav, V., et al. (2019). *A Manual for Community Fish Refuge-Rice Field Fisheries System Management in Cambodia*. Phnom Penh: Fisheries Administration and WorldFish Cambodia.

Koohafkan, P., and Furtado, J. (2004). "Traditional rice fish systems and globally indigenous agricultural heritage systems," in *FAO Rice Conference.* Available online at: http://www.fao.org/3/y5682e/y5682e0b.htm

Liu, Y., Duan, M., and Yu, Z. (2013). Agricultural landscapes and biodiversity in China. *Agric. Ecosyst. Environ.* 166, 46–54. doi: 10.1016/j.agee.2011.05.009

Lu, J., and Li, X. (2006). Review of rice-fish-farming systems in China - one of the globally important ingenious agricultural heritage systems (GIAHS). *Aquaculture* 260, 106–113. doi: 10.1016/j.aquaculture.2006.05.059

MAFF (2014). *Cambodia Climate Change Priorities Action Plan for Agriculture, Forestry and Fisheries Sector 2014-2018*. Phnom Penh: Ministry of Agriculture, Forestry, and Fisheries.

MAFF (2017). *Annual Report of Agriculture, Forestry and Fisheries 2016-2017 and Directions 2017-2018*. Phnom Penh: Ministry of Agriculture, Forestry, and Fisheries.

MAFF (2018). *Annual Report 2017-18 and Directions for 2018-19.* Phnom Penh: Ministry of Agriculture, Forestry, and Fisheries.

Magrini, M.-B., Anton, M., Chardigny, J.-M., Duc, G., Duru, M., Jeuffroy, M.-H., et al. (2018). Pulses for sustainability: breaking agriculture and food sectors out of lock-in. *Front. Sustain. Food Syst.* 2, 1–17. doi: 10.3389/fsufs.2018.00064

McCartney, M. P., Whiting, L., Makin, I., Lankford, B. A., and Ringler, C. (2019). Rethinking irrigation modernisation: realising multiple objectives through the integration of fisheries. *Mar. Freshw. Res.* 70, 1265–1273. doi: 10.1071/MF19161

Meynard, J. M., Charrier, F., Fares, M., Le Bail, M., Magrini, M. B., Charlier, A., et al. (2018). Socio-technical lock-in hinders crop diversification in France. *Agron. Sustain. Dev.* 38:54. doi: 10.1007/s13593-018-0535-1

Miao, W. (2010). "Recent developments in rice-fish culture in China: a holistic approach for livelihood improvement in rural areas," in *Success stories in Asian aquaculture*, eds S. S. De Silva and F. B. Davy (Dordrecht: Springer), 15–40. doi: 10.1007/978-90-481-3087-0_2

Miao, W. (2016). Highlights of regional initiative for blue growth in Asia-Pacific. *FAO Aquac. Newslett.* 54, 20–21. Rome: Food and agriculture organisation of the United Nations.

Minderhoud, P., Erkens, G., Pham, V., Bui, V., Erban, L., Kooi, H., et al. (2017). Impacts of 25 years of groundwater extraction on subsidence in the Mekong Delta, Vietnam. *Environ. Res. Lett.* 12:064006. doi: 10.1088/1748-9326/aa7146

Mukherji, A., Facon, T., Burke, J., de Fraiture, C., Faurès, J., Füleki, B., et al. (2009). *Revitalizing Asia's Irrigation: To Sustainably Meet Tomorrow's Food Needs.* Colombo: International Water Management Institute; Rome: Food and Agriculture Organization of the United Nations.

Myers, S. S., Smith, M. R., Guth, S., Golden, C. D., Vaitla, B., Mueller, N. D., et al. (2017). Climate change and global food systems: potential impacts on food security and undernutrition. *Annu. Rev. Public Health* 38, 259–277. doi: 10.1146/annurev-publhealth-031816-044356

Nasielski, J., Kc, K. B., Johnstone, G., and Baran, E. (2016). When is a fisher (not) a fisher? Factors that influence the decision to report fishing as an occupation in rural Cambodia. *Fish. Manag. Ecol.* 23, 478–488. doi: 10.1111/fme.12187

Nguyen Khoa, S., Lorenzen, K., Garaway, C., Chamsinhg, B., Siebert, D., and Randone, M. (2005). Impacts of irrigation on fisheries in rain-fed rice-farming landscapes. *J. Appl. Ecol.* 42, 892–900. doi: 10.1111/j.1365-2664.2005.01062.x

Nguyen, V. K., Dumaresq, D., and Pittock, J. (2018). Impacts of rice intensification on rural households in the Mekong Delta: emerging relationships between agricultural production, wild food supply and food consumption. *Food Secur.* 10, 1615–1629. doi: 10.1007/s12571-018-0848-6

Nguyen, V. K., Nguyen, H. H., and Cramb, R. (2020). "Trends in rice-based farming systems in the Mekong delta," in *White Gold: The Commercialization of Rice Farming in Lower Mekong Basin*, ed R. Cramb (Singapore: Palgrave Macmillan), 347–373.

Nhan, D. K., Trung, N. H., and Van Sanh, N. (2011). "The impact of weather variability on rice and aquaculture production in the mekong delta," in *Environmental Change and Agricultural Sustainability in the Mekong Delta. Advances in Global Change Research*, Vol. 45, eds M. Stewart, and P. Coclanis (Dordrecht: Springer). doi: 10.1007/978-94-007-0934-8_24

Oo, A. T., Huylenbroeck, G. Van Huylenbroeck, G., and Speelman, S. (2018). Assessment of climate change vulnerability of farm households in Pyapon District, a delta region in Myanmar. *Int. J. Disaster Risk Reduct.* 28, 10–21. doi: 10.1016/j.ijdrr.2018.02.012

Oo, S. M., and Mackay, K. T. (2018). Small-scale aquaculture of wild fish in Myanmar: a preliminary report from the Bago region. *Aquac. Asia Magazine* 22, 19–26.

Pingali, P. L. (2012). Green revolution: impacts, limits, andthe path ahead. *Proc. Natl. Acad. Sci. U.S. A.* 109, 12302–12308. doi: 10.1073/pnas.0912953109

Ponte, S., Kelling, I., Jespersen, K. S., and Kruijssen, F. (2014). The blue revolution in asia: upgrading and governance in aquaculture value chains. *World Dev.* 64, 52–64. doi: 10.1016/j.worlddev.2014.05.022

Rahman, A., Quddus, A., Pokrant, B., and Ali, M. (2006). *Shrimp Farming and Industry: Sustainability, Trade and Livelihoods*. Dhaka: Bangladesh Center for Advanced Studies and the University Press Limited.

Raihan, M. L., Onitsuka, K., Basu, M., Shimizu, N., and Hoshino, S. (2020). Rapid emergence and increasing risks of hailstorms: A potential threat to sustainable agriculture in Northern Bangladesh. *Sustain.* 12:5011. doi: 10.3390/su12125011

Raitzer, D., Wong, L., and Samson, J. (2015). Myanmar's agriculture sector: unlocking the potential for inclusive growth. *Asian Development Bank Economics Working Paper Series No. 470.* Available online at: https://ssrn.com/abstract=2709353

Ratner, B. D., and Allison, E. H. (2012). Wealth, rights, and resilience: an agenda for governance reform in small-scale fisheries. *Dev. Policy Rev.* 30, 371–398. doi: 10.1111/j.1467-7679.2012.00581.x

Reardon, T., and Timmer, C. P. (2014). Five inter-linked transformations in the Asian agrifood economy: food security implications. *Glob. Food Sec.* 3, 108–117. doi: 10.1016/j.gfs.2014.02.001

RGC (2008). *Rectangular Strategy for Growth, Employment, Equity, and Efficiency*. Phnom Penh.

Robertson, B., Young, P., Kristensen, J., Cho, K. M., Thwe, H. M., Pannchi, M., et al. (2018). *Strategic Review of Food and Nutrition Security in Myanmar: "In Support of Sustainable Development Goal (SDG) 2-Roadmap to 2030"*. Nay Pyi Taw: Myamar Institutie for Integrated Development. Available online at: https://docs.wfp.org/api/documents/WFP-0000073885/download/ (accessed October 19, 2020).

Ruddle, K. (1982). Traditional integrated farming systems and rural development: the example of ricefield fisheries in Southeast Asia. *Agric. Adm.* 10, 1–11. doi: 10.1016/0309-586X(82)90036-X

Schipanski, M. E., MacDonald, G. K., Rosenzweig, S., Chappell, M. J., Bennett, E. M., Kerr, R. B., et al. (2016). Realizing resilient food systems. *Bioscience* 66, 600–610. doi: 10.1093/biosci/biw052

Shankar, B., Halls, A., and Barr, J. (2005). The effects of surface water abstraction for rice irrigation on floodplain fish production in Bangladesh. *Int. J. Water* 3, 61–83. doi: 10.1504/IJW.2005.007159

Sheriff, N., Joffre, O., Hong, M., Barman, B., Haque, A., Rahman, F., et al. (2010). *Community-Based Fish Culture in Seasonal Floodplains and Irrigations Systems. Challenge Programme on Water and Food (CPWF)*. Project Report, Project Number CP35, 120. Available online at: https://www.worldfishcenter.org/content/community-based-fish-culture-seasonal-floodplains-and-irrigation-systems-0 (accessed October 19, 2020).

Sinclair, F., and Coe, R. I. C. (2019). The options by context approach: a paradigm shift in agronomy. *Exp. Agric.* 55, 1–13. doi: 10.1017/S0014479719000139

Sinclair, F., Wezel, A., Mbow, C., Chomba, S., Robiglio, V., and Harrison, R. (2019). *The Contribution of Agroecological Approaches to Realizing Climate-Resilient Agriculture*. Background Paper. Rotterdam; Washington, DC: Global Commission on Adaptation.. Available online at: https://cdn.gca.org/assets/2019-12/TheContributionsOfAgroecologicalApproaches.pdf (accessed October 19, 2020).

South China Morning Post (2020). *Drought drives Vietnam's Mekong Delta to Declare State of Emergency*. Available online at: https://www.scmp.com/news/asia/southeast-asia/article/3074064/drought-drives-vietnams-mekong-delta-declare-state (accessed October 19, 2020).

Stür, W., Gray, G. D. (2015) "Livestock in smallholder farming systems of mainland Southeast Asia," in *Trajectories of Rice-Based Farming Systems in Mainland Southeast Asia*, ed R. Cramb (Canberra, ACT: Australian Centre for International Agricultural Research), 139–188.

Taki, Y. (1975). Fish Fauna and Inland Fisheries of the Mekong Delta. *South East Asian Stud.* 13, 146–160.

Tezzo, X., Belton, B., Johnstone, G., and Callow, M. (2018). Myanmar's fisheries in transition: current status and opportunities for policy reform. *Mar. Policy* 97, 91–100. doi: 10.1016/j.marpol.2018.08.031

Tezzo, X., Bush, S. R., Oosterveer, P., and Belton, B. (2020). Food system perspective on fisheries and aquaculture development in Asia. *Agric. Human Values*. doi: 10.1007/s10460-020-10037-5

Thang, T. (2017). *Current Status of Vietnam Rice Export Quality*. Taipei: FFTC Agricultural Policy Platform. Available online at: https://ap.fftc.org.tw/article/1204 (accessed October 19, 2020).

Thangrak, V., Somboonsuke, B., Sdoodee, S., Darnsawasdi, R., and Voe, P. (2020). The smallholder farmers' perceptions of climate variability impact on rice production and the case of adaptation strategies in Banteay Meanchey, (BMC), Cambodia. *Int. J. Agric. Technol.* 16, 505–516.

The World Bank (2017a). *Cambodia - Sustaining Strong Growth for the Benefit of All*. Available online at: https://openknowledge.worldbank.org/handle/10986/27149# (accessed October 19, 2020). doi: 10.1596/27149

The World Bank, (2017b). *World Development Indicators Database*. Available online at: https://data.worldbank.org/indicator/NY.GNP.PCAP.PP.CD (accessed October 19, 2020).

Therond, O., Duru, M., Roger-Estrade, J., and Richard, G. (2017). A new analytical framework of farming system and agriculture model diversities. *A review. Agron. Sustain. Dev.* 37:21. doi: 10.1007/s13593-017-0429-7

Thilsted, S. H., Thorne-Lyman, A., Webb, P., Bogard, J. R., Subasinghe, R., Phillips, M. J., et al. (2016). Sustaining healthy diets: the role of capture fisheries and aquaculture for improving nutrition in the post-2015 era. *Food Policy* 61, 126–131. doi: 10.1016/j.foodpol.2016.02.005

Tilman, D. (1998). The greening of the green revolution. *Nature* 396, 211–212. doi: 10.1038/24254

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., and Polasky, S. (2002). Agricultural sustainability and intensive production practices. *Nature* 418, 671–677. doi: 10.1038/nature01014

Tirol-Padre, A., Minamikawa, K., Tokida, T., Wassmann, R., and Yagi, K. (2018). Site-specific feasibility of alternate wetting and drying as a greenhouse gas mitigation option in irrigated rice fields in Southeast Asia: a synthesis. *Soil Sci. Plant Nutr.* 64, 2–13. doi: 10.1080/00380768.2017.1409602

Tong, Y. D. (2017). Rice intensive cropping and balanced cropping in the Mekong Delta, Vietnam — economic and ecological considerations. *Ecol. Econ.* 132, 205–212. doi: 10.1016/j.ecolecon.2016.10.013

Toufique, K. A., and Gregory, R. (2008). Common waters and private lands: distributional impacts of floodplain aquaculture in Bangladesh. *Food Policy* 33, 587–594. doi: 10.1016/j.foodpol.2008.04.001

Troell, M., Naylor, R. L., Metian, M., Beveridge, M., Tyedmers, P. H., Folke, C., et al. (2014). Does aquaculture add resilience to the global food system? *Proc. Natl. Acad. Sci. U.S. A.* 111, 13257–13263. doi: 10.1073/pnas.1404067111

UNDP (2020). *Human Development Data*. Available online at: http://hdr.undp.org/en/data# (accessed October 19, 2020).

Vo, X. (1975). Rice cultivation in the Mekong Delta present situation and potentials for increased production. *Southeast Asian Stud.* 13, 88–111.

Vu, H. (2012). *Moral Economy Meets Global Economy: Negotiating Risk, Vulnerability and Sustainable Livelihood among Shrimp Farming Households in Vietnam's Mekong Delta*. Available online at: https://surface.syr.edu/ant_etd/98 (accessed October 19, 2020).

Vyas, S., Kov, P., Smets, S., and Spears, D. (2016). Disease externalities and net nutrition: evidence from changes in sanitation and child height in Cambodia, 2005–2010. *Econ. Hum. Biol.* 23, 235–245. doi: 10.1016/j.ehb.2016.10.002

Welcomme, R., and Bartley, D. (1998). Current approaches to the enhancement of fisheries. *Fish. Manag. Ecol.* 5, 351–382. doi: 10.1046/j.1365-2400.1998.550351.x

WHO (2016). *Global Health Observatory Data Repository/World Health Statistics*. World Bank; World Health Organization. Available online at: https://data.worldbank.org/indicator/SH.PRG.ANEM

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., et al. (2019). Food in the Anthropocene: the EAT lancet commission on healthy diets from sustainable food systems. *Lancet* 393, 447–492. doi: 10.1016/S0140-6736(18)31788-4

Wilson, S., and Wai, N. (2013). *Food and Nutrition security in Myanmar*. East Lansing: Michigan State University; Yangon: Myanmar Development Resource Institute, Centre for Economic and Social Development (MDRI-CESD).

World Bank (2018). *Navigating Risks, Myanmar Economic Monitor*. Washington, DC: World Bank. Available online at: http://documents1.worldbank.org/curated/en/986461544542633353/pdf/132847-REVISED-MEM-Final.pdf (accessed October 19, 2020).

World Bank Group (2015). *Bangladesh: More and Better Jobs to Accelerate Shared Growth and End Extreme Poverty. Systematic Country Diagnostic*. World Bank, Washington, DC. Available online at: https://openknowledge.worldbank.org/handle/10986/23101 (accessed 19 October 2020).

Xie, J., Hu, L., Tang, J., Wu, X., Li, N., Yuan, Y., et al. (2011). Ecological mechanisms underlying the sustainability of the agricultural heritage rice-fish coculture system. *Proc. Natl. Acad. Sci. U.S. A.* 108, E1381–E1387. doi: 10.1073/pnas.1111043108

Zhang, D., Min, Q., Liu, M., and Cheng, S. (2012). Ecosystem service tradeoff between traditional and modern agriculture: a case study in Congjiang County, Guizhou province, China. *Front. Environ. Sci. Eng. China* 6, 743–752. doi: 10.1007/s11783-011-0385-4

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METHODS
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Assessing Transitions to Sustainable Agricultural and Food Systems: A Tool for Agroecology Performance Evaluation (TAPE)

Anne Mottet [1]*, *Abram Bicksler* [1], *Dario Lucantoni* [1], *Fabrizia De Rosa* [1], *Beate Scherf* [1], *Eric Scopel* [2], *Santiago López-Ridaura* [3], *Barbara Gemmil-Herren* [4], *Rachel Bezner Kerr* [5], *Jean-Michel Sourisseau* [2], *Paulo Petersen* [6], *Jean-Luc Chotte* [7], *Allison Loconto* [1,8] and *Pablo Tittonell* [2,9,10]

[1] Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, [2] Centre de coopération internationale en recherche agronomique pour le développement (CIRAD), Montpellier, France, [3] International Maize and Wheat Improvement Center (CIMMYT), Texcoco, Mexico, [4] World Agroforestry Centre (ICRAF), Nairobi, Kenya, [5] Department of Global Development, Cornell University, Ithaca, NY, United States, [6] Agricultura Familiar e Agroecologia (AS-PTA), Rio de Janeiro, Brazil, [7] Eco&Sols Joint Research Unit, Institut de recherche pour le développement (IRD), Montpellier, France, [8] Laboratoire Interdisciplinaire Sciences Innovations Sociétés (UMR LISIS 1326—CNRS, ESIEE, INRAE, UGE), Institut national de recherche pour l'agriculture, l'alimentation et l'environnement (INRAE), Université Gustave Eiffel, Marne-la-Vallée, France, [9] Grupo Interdisciplinario de Investigación-Extensión en Agroecología, Ambiente y Sistemas de Producción (GIAASP), Instituto Nacional de Tecnología Agropecuaria (INTA), San Carlos de Bariloche, Argentina, [10] Institute of Evolutionary Life Sciences (GELIFES), Groningen University, Groningen, Netherlands

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***Correspondence:**
Anne Mottet
anne.mottet@fao.org

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There is increasing interest in agroecology as a way to move toward more sustainable agriculture and food systems. However, the evidence of agroecology's contribution to sustainability remains fragmented because of heterogeneous methods and data, differing scales and timeframes, and knowledge gaps. Facing these challenges, 70 representatives of agroecology-related organizations worldwide participated in the development of the Tool for Agroecology Performance Evaluation (TAPE), to produce and consolidate evidence on the multidimensional performances of agroecological systems. TAPE is composed of: Step 0, the preliminary step that includes a description of the main socio-economic and demographic characteristics of the agricultural and food systems and an analysis of the enabling environment in terms of relevant policy, market, technology, socio-cultural and/or historical drivers; Step 1, the Characterization of Agroecological Transitions (CAET), based on the 10 Elements of Agroecology adopted by FAO and its member countries, using descriptive scales to establish scores and assessing the degree of transition, with information from the farm/household and community/territory scale; Step 2, the Core Criteria of Performance listing the key dimensions considered relevant to address the Sustainable Development Goals (SDGs): Environment & climate change; Health & nutrition; Society & culture; Economy and Governance. Finally Step 3, a participatory validation of the results obtained from the previous steps with the producers and relevant stakeholders. TAPE can be used (i) to assess the extent of agroecological transition among agricultural producers in a community or a territory, (ii) to monitor and evaluate projects by characterizing the initial and subsequent steps in an agroecological transition, and/or (iii) to evaluate widely diverse agricultural systems against agroecological elements and how they contribute to the achievement of the SDGs. Its application can support the transition of all forms of agricultural systems toward more sustainable practices and the formulation of adequate policies to enable this transformation. Preliminary results from pilot applications show that TAPE can perform in a variety of geographic regions and agroecosystems and that it allows assessment of performances of various criteria that move beyond classic indicators to begin to build a global evidence base for agroecology and support transformation to sustainable agricultural production and food systems.

Keywords: agroecolgy, sustainability assessment framework, indicators, multicriteria evaluation, farm, territory, participatory process

INTRODUCTION

The global food system is facing environmental, social, and health challenges. While nature and ecological principles were applied by family farmers for millenia, agriculture became increasingly dependent on external inputs, including synthetic fertilizers, in the last century, particularly in large scale production systems. Agroecology is an alternative and systemic approach that builds on local and ecological knowledge, enhances social capital and confronts the proliferation of agrochemical inputs (HLPE, 2019). This approach is at the same time a scientific field, a set of agricultural practices and a social movement (Wezel et al., 2009). Since its origins in the 1930's when scientists started to use the term agroecology to refer to the application of ecological principles to agriculture, its scale and dimensions have grown tremendously (Altieri, 2002, 2018; Ollivier and Bellon, 2013). With an initial scope of studying the production system, agroecology extended to cover the larger agroecosystem and, more recently, to the level of a food system, including agri-food supply chains and consumption patterns (Gliessman, 2015). Due to this long history, tripartite origin, systemic scope and transformational aspiration, agroecology presents a promising approach for shifting toward more sustainable food systems.

As agroecology has been increasingly brought into the international dialogue on the future of food and agricultural production, there have been calls for building the evidence base of its performance across its multiple dimensions. Over the last decade, a growing body of literature has demonstrated the positive impacts of agroecology, on several aspects: environment (Francis et al., 2003; Gliessman, 2015; Modernel et al., 2018); food and nutrition security (Luna-González and Sørensen, 2018; Deaconu and Mercille, 2019; Kerr et al., 2019a) and on households' incomes (D'Annolfo et al., 2017; Van der Ploeg et al., 2019).Yet these results remain fragmented due to heterogeneous methods and data, differing scales, contexts, and timeframes. Since agroecology is generating growing political interest for its potential to make our food systems more sustainable, there is a need for global and comparable evidence on its multidimensional performance at the different scales of agroecological practices that can be used to inform policy-making processes. This evidence needs to be co-constructed with a diversity of actors, operating at different scales, timeframes, and contexts, and dovetailed into their existing work. It also should be able to contribute to evaluating a wide range of agricultural systems against the 10 Elements of Agroecology approved by FAO member nations (FAO, 2018a; Barrios et al., 2020). This need for evidence has been expressed at the intergovernmental level, by the 26th Committee on Agriculture of the United Nations Food and Agriculture Organization (COAG, 2018), and also by the High Level Panel of Experts of the multi-stakeholder Committee on Food Security (HLPE, 2019).

In response to this call, FAO coordinated the participatory development of the Tool for Agroecology Performance Evaluation (TAPE), whose general objective is to produce consolidated evidence on the extent and intensity of the use of agroecological practices and the performance of agroecological systems across five dimensions of sustainability: (i) environment, (ii) social and cultural, (iii) economic, (iv) health and nutrition, and (v) governance. These five dimensions were identified as priorities during the consultative process. They include the three pillars of the initial definition by the Brundtland Commission (economic, social, and environmental) as well as two additional dimensions of particular relevance for policy makers in the area of food and agriculture, which were also included by other frameworks for the assessment of agricultural sustainability: governance (see for example SAFA (FAO, 2014) and nutrition [see e.g., (Peano et al., 2014), RHoMIS (Herrero et al., 2017), or IDEA (Zahm et al., 2008)].

This paper was prepared by the FAO coordination team and a number of the members of the technical working group that supported the development of the TAPE. The paper presents TAPE and the methodological choices that were made through the process of co-development. These relate to: the scale of assessment, the diversity of production systems to consider at the global level, and the multicriteria and integrated nature of the evaluation. We argue that such a tool can contribute to the assessment of the sustainability of our agricultural and food systems in a multidimensional manner and in a variety of contexts. We also argue that its application can support the transition toward more sustainable food systems. We illustrate the use of the tool for different types of applications, from project monitoring to regional assessments or comparative analysis, and in different geographical contexts.

METHODS

Process of Development and Participants

The development process of TAPE was coordinated by FAO and included (i) a review of existing frameworks and indicators for assessing sustainability in agriculture, (ii) a participatory and inclusive multi-stakeholder consultation phase based on a review and prioritization of over 70 indicators by more than 450 participants over 4 months and (iii) an international in-person workshop with 70 participants from academia, non-profit, government, social movement, private sector, and from international organizations. After this workshop, a technical working group of 16 people was formed, including scientists and civil society representatives working on agroecology in different parts of the world. The technical working group in collaboration with the FAO coordination team further developed an analytical framework upon which an operable tool could be built to assess performance indicators that go beyond standard measures of productivity (e.g., yield/ha) and that better represent the benefits and trade-offs associated with different types of agricultural systems (FAO, 2019a). This work benefited from the expertise of the technical working group members in assessing sustainability in agriculture and food systems and in implementing agroecology projects. This process contributed to their work by providing them with a global platform to showcase projects and results and with an opportunity to reflect on their approach of agroecology and better coordinate with other on-going initiatives. TAPE is currently being pilot tested in over 10 countries, including Cambodia, China, Laos, Vietnam, Mexico, Peru, Argentina, Nicaragua, Senegal, Mali, Tanzania and Spain. Its final version will include feedback from these pilot assessments. Pilot assessments require initial training of enumerators which have been carried out both in person and in remote form, with a duration varying from 8 h to 2 days.

Founding Principles and Key Attributes of TAPE

Twenty founding principles were agreed upon during the participatory process of TAPE's development, which cover:

a) Processes: building on existing frameworks and datasets; using approaches for both sector-specific and integrated production systems; testing the tool with partners involving producers;
b) Scope of the tool: globally applicable; producing evidence at various scales, using the farm/household as assessment unit but collecting information and being relevant at the community/territory level;
c) Relevance of the evidence produced: linking closely with the SDGs; informing global sustainability challenges; and
d) Characteristics of the tool and methodological choices: simplicity, requiring minimum data collection, but extendable; scientifically robust but operationally flexible; characterizing agroecological transitions using the 10 Elements of Agroecology (FAO, 2018a) and evaluating the performance of the systems using objective indicators.

Reviews of sustainability assessment frameworks usually conclude that there is no one-size-fits-all solution (Schader et al., 2014) and that the method that is most suitable to the context and the evaluation process should be selected (Cândido et al., 2015; De Olde et al., 2016). Our non-exhaustive review of existing frameworks and consultation with experts led to the definition of key attributes for TAPE to respond to the mandate given, which are summarized in **Table 1**. These key attributes also respond to the founding principles described above.

In particular, the Evaluation of Natural Resource Management Systems, or MESMIS by its Spanish acronym, inspired the team to take a stepwise approach for TAPE. MESMIS is a reference evaluation framework commonly used in Latin America, which provides principles and guidelines for the derivation, quantification and integration of context-specific indicators through a participatory process involving local actors. The MESMIS evaluation cycle features an inextricable link between system evaluation, system design, and system improvement (López-Ridaura et al., 2002).

The stepwise approach adopted in TAPE is summarized in **Figure 1**. It is based on two central steps (1 and 2) that consist of assessing the level of agroecological transitions and quantifying impacts on the core criteria of performance. While Step 1, based on the 10 Elements of Agroecology, provides a diagnostic on where the system stands in terms of its transition toward sustainability, Step 2 measures in quali-quantitative terms the impact of agroecological systems on the various dimensions of sustainability. This duality is a response to one of the basic principles identified during the consultation phase. The two core steps are complemented by a preliminary description of the context (step 0), with the facultative inclusion of a typology of transitions (step 1 bis), and a final analysis and participatory interpretation of results (step 3). The 2 core steps (Step 1 and 2) can be undertaken with an electronic survey form, using KoBoToolbox[1], a suite of free and open source tools for field data collection specially developed for humanitarian work and challenging environments. This tool directly populates a central database. Step 1 and Step 2 can be undertaken simultaneously in the field and will take a maximum of 3 h, but they can also be carried out in two separate visits of ∼1 h and 2 h.

When assessing agroecological systems at farm scale, a sample of respresentative farms/households within the same territory or landscape across a spectrum of production systems should be included in the survey in order to create inference spaces on the relative performance of these systems (Section Scale of Assessment, Data Collection, and Sampling Methodology). If these units are homogeneous and meet other statistical robustness parameters, they may be aggregated to then provide

[1] Available online at: https://www.kobotoolbox.org/

TABLE 1 | Main key attributes retained from a number of existing frameworks reviewed and main differences between those frameworks and TAPE.

Framework	Main key attributes retained	Main differences
MESMIS—Marco para la Evaluacíon de Sistemas de Manejo de recursos naturales incorporando Indicadores de Sostenibilidad (GIRA-UNAM) (López-Ridaura et al., 2002)	• Participatory • Step-wise hierarchical • Flexible • Starts with contextualization	• Indicators can be quantified by different methods vs. recommended harmonized protocols are provided in TAPE
GTAE—Groupe de Travail sur les Transitions Agroécologiques (CIRAD-IRD-AgroParistech)—Memento pour l'évaluation de l'agroécologie (Levard et al., 2019)	• Simple and not unreasonably time consuming • Allows integration in broader systems of monitoring and evaluation • Most criteria are shared with TAPE and two criteria use the same methods	• Initial step of complete agrarian diagnostic not included in TAPE • Some GTAE criteria are proposed as optional advanced criteria in TAPE as they require more time and resources
SOCLA—Sociedad Científica Latinoamericana de Agroecología, Method to assess sustainability and resilience in farming (Nicholls et al., 2004)	• Participatory and simple • Soil health assessment used as core criteria in TAPE • Almost all other criteria are common	• In depth crop health assessment not included in TAPE, can be used as advanced criteria
Sustainable Intensification Assessment Framework (Musumba et al., 2017)	• No focus on particular practices • Addresses different scales (field/ animal, farm/household, community/ territory) • 6 domains of sustainability are aligned with the 5 dimensions of TAPE	• Some of the criteria/indicators are included as advanced criteria in TAPE
LUME—a method for the economic-ecological analysis of agroecosystems (Petersen et al., 2020)	• Participatory • Starts with contextualization • Qualitative and quantitative evaluations • Values the non-monetary economy	• Analyzes the economic performance of agroecosystems by combining degrees of autonomy and productivity of the production factors (land and labor) • Specifies the degree of social integration of farming families in the territorial socio-technical networks
Measuring the impact of ZBNF, the Zero Budget Natural Farming and (LVC, 2016)	• Participatory and possible self-assessment • Large number of common indicators /impact	• Method largely left to implementer to define while TAPE provides recommended protocols
The Economics of Ecosystems and biodiversity—(TEEB, 2018)	• Separates 2 steps: description of the system and analysis of the impacts • 4 dimensions of impacts included (and TAPE adds a 5th)	• Economic assessment based on 4 capitals, which is not the entry point in TAPE
Sustainable Rural Livelihoods approach (Sourisseau, 2014)	• Includes an analysis of the context (institutions, household activities…) • The qualification of assets provides an option to integrate the 10 Elements within TAPE	• Not participatory
Participatory methodologies from Malawi and Tanzania (Kerr et al., 2019c)	• Assessing systems in transition • Participatory and based on interviews	• Indicators left to implementer to define while TAPE provides recommended protocols
SAFA–Sustainability Assessment of Food and Agriculture systems (FAO, 2014)	• Includes 4 dimensions of sustainability (environment, social, economic and governance), and TAPE adds a 5^{th} (health and nutrition) • Aims to be global and applicable to all types of production systems	• Time consuming (21 themes and 58 sub-themes, 118 indicators) while TAPE is simple and not unreasonably time consuming • Targets enterprises (farms or companies) while TAPE targets farms and communities
Rural Household Multi-Indicator Survey (RHoMIS) (Herrero et al., 2017)	• Works at household level • Large number of common indicators in Step 2	• TAPE starts with an analysis of the enabling environment and follows with a diagnostic of the agroecological transition before looking at performances
(Indicateurs de Durabilité des Exploitations Agricoles or Indicatorsof Sustainable Farm Development (IDEA) (Zahm et al., 2008)	• Step-wise hierarchical • Specific quantitative indicators • 28 out 41 IDEA indicators are shared with TAPE • Can be used as self-assessment tool	• Three main dimensions of sustainability in IDEA are included in TAPE + two additional ones • TAPE includes context, enabling environment and level of transition before quantitative assessment

a "snapshot" at a territorial level of the overall performance of the systems.

Scale of Assessment, Data Collection, and Sampling Methodology

While the elementary unit for agricultural management is the farm/household, the territory/community is the scale at which a number of processes necessary for the agroecological transition take place (Gliessman, 2015). In TAPE, the farm/household is the elementary unit of measure, but as in any systems approach immediate lower (e.g., plot, herd) and higher (landscape, territory or community) levels need to be considered and results made relevant at such levels. In this article we focus mostly on asessments at farm/household level, as the current versions of the analytical tool and e-forms are ready, available and operable at this scale. Specific methods for better including

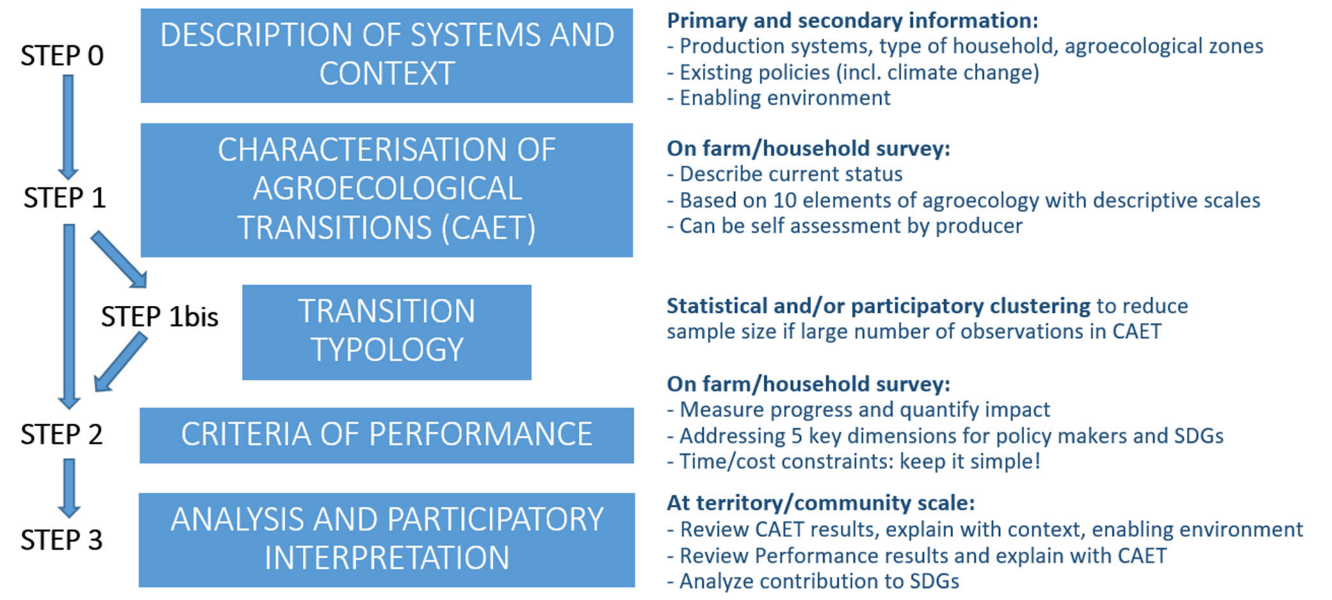


FIGURE 1 | The stepwise approach for implementing the Tool for Agroecology Performance Evaluation (TAPE) (FAO, 2019a).

agroecological transitions and performance at higher levels (community, region, etc.) are under construction to complement the current farm-level tool. Step 0 integrates context and enabling environment information from wider scales, such as the regional or national if relevant. Similarly, as for completing Step 1 (Characterization of Agroecological Transition—CAET), enumerators also need to take into account some features of the productive systems at the community or territorial level (especially for assessing the elements of Co-creation and Sharing of Knowledge, Circular and Solidarity Economy and Responsible Governance). Data collection for Step 2 (Core criteria of performance) is conducted at the farm/household level, with information specifically collected from individuals (both women and men), but results can be aggregated to the territory/community level, in particular in the case of the application of Step 1 bis, the typology of transitions to reduce the size of the sample of systems to be assessed based on the result of the CAET (Step 1).

Aggregation at higher scales requires carefully defined farm sampling methods, closely related with the objectives of the analysis (more information is provided in the **Supplementary Information**). A stratified or purposive sampling may be used. Farms and/or household units are sampled within the same territory to provide a territorial snapshot (i.e., making deductions about a particular territorial population using some form of sampling drawn from that population) under the assumption that units belonging to the same territory are more similar to each other than units in different territories. Therefore, it is hoped that the majority of differences between observations (variance) belonging to the same territorial group should come from their level of application of practices. This methodology can be adapted to any level of analysis; in fact, the generic terms 'region' or 'territory' may refer here to different strata such as a municipality, a watershed, a province, an administrative region, or any other defined area.

DESCRIPTION OF ASSESSMENT STEPS

Step 0—Systems and Context

Recognizing that any assessment of performance should be placed in its specific context, Step 0 is a preliminary step that collects information from the territorial, regional and national levels. This step is first conducted as a desk review using a template with a common core set of questions that includes: a description of the main territory of interest in which TAPE will be used, demographic characteristics of farms/households in that territory, descriptions of the ecological environment, descriptions of the social and productive environment and of the market structure in the territory, and descriptions of the enabling environment for agroecology. The enabling environment can include a listing of public policies at national, state/province, and local levels that can support or hinder the transition to agroecology, and the existence of local actors, groups or networks and educational institutions that can support the agroecological transition of local producers. It can also include elements of local economy and power relations between actors that can influence opportunities for farmers or cooperatives. Beyond simply listing these attributes, stakeholders completing this step (e.g., enumerators, CSO workers, government agents, academics, etc.) can provide evidence, links, and secondary information (published literature and existing meta-data, such as reports by government and UN organizations, national statistics, CSO project documents etc.) to support this step. In addition to implementation via a desk review, this step can also include a

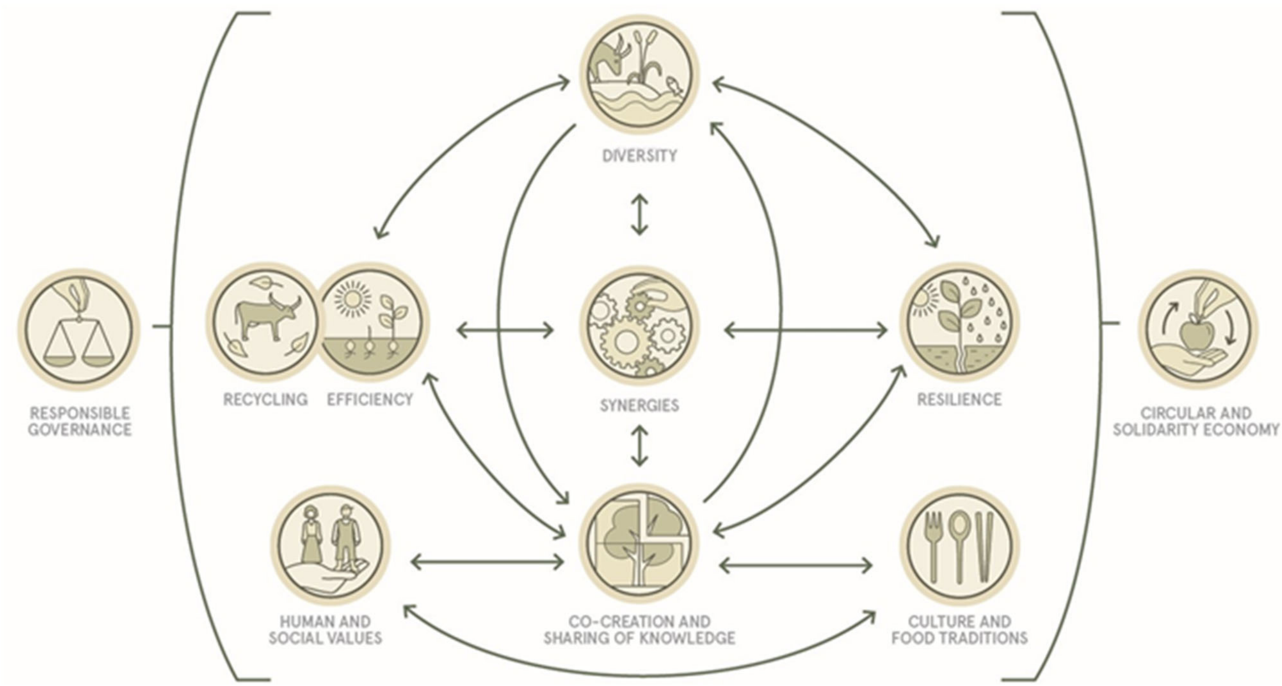


FIGURE 2 | The 10 Elements of Agroecology (FAO, 2018a).

TABLE 2 | Characterization of agroecological transitions (CAET): Descriptive scales and scores for the element "Diversity."

	Index	0	1	2	3	4
DIVERSITY	**Crops**	Monoculture (or no crops cultivated)	One crop covering more than 80% of cultivated area	Two or three crops	More than 3 crops adapted to local and changing climatic conditions	More than 3 crops and varieties adapted to local conditions. Spatially diversified farm by multi-, poly- or inter-cropping
	Animals (including fish and insects)	No animals raised	One species only	Several species, with few animals	Several species with significant number of animals	High number of species with different breeds well-adapted to local and changing climatic conditions
	Trees (and other perennials)	No trees (nor other perennials)	Few trees (and/or other perennials) of one species only	Some trees (and/or other perennials) of more than one species	Significant number of trees (and/or other perennials) of different species	High number of trees (and/or other perennials) of different species integrated within the farm land
	Diversity of activities, products and services	One productive activity only (e.g., selling only one crop)	Two or three productive activities (e.g., selling two crops, or one crop and one type of animals)	More than 3 productive activities	More than 3 productive activities and one service (e.g., processing products on the farm, ecotourism, transport of agricultural goods, training etc.)	More than 3 productive activities, and several services

semi-structured consultation with key stakeholders, in the form of a workshop for example.

Several key indicators of Step 0 are also collected at the producer level as part of the survey. These data include the location of the farm/household (with geolocation), size of the farm, basic demographics of the household, market access, etc.

The detailed templates for Step 0 are provided in **Supplementary Information**.

Step 1 — Characterization of Agroecological Transition (CAET)

Step 1 consists of characterizing the degree of transition to agroecology of agricultural systems (e.g., farms/households, communities/territories) based on the 10 Elements of Agroecology (**Figure 2**). It can be completed as a guided exercise with intermediaries or as through a self-assessment by producers after initial capacity building.

The 10 Elements are used as criteria to define semi-quantitative indices that take the form of descriptive scales with scores from 0 to 4. As an example, **Table 2** provides the relevant indices for the element "Diversity," which are: (i) Diversity of crops, (ii) Diversity of animals, (iii) Diversity of trees, and (iv) Diversity of activities, products and services. The scores of each index for this element range from 0 to 4, depending on how diversified the production is. The scores of the four indices are summed (e.g., 2+3+3+4 = 12) and the totals are standardized on a scale from 0 to 100% (12/16 = 75%) to obtain the general score for the element "Diversity."

The same method is applied to all 10 Elements. While no prescriptive threshold is defined, systems with high scores across all 10 Elements are considered already well-progressed in their agroecological transition. Each element is described with three or four indices, for a total number of indices to be scored in the CAET of 36. Indices for the other nine elements are presented in **Table 3** and descriptive scales are provided in **Supplementary Information**. Step 1 requires a participatory preliminary translation in the local context as the five different scale for each index should describe the current and possible future positions of agroecological systems in each territory. It can be completed as a self-assessment by producers or community leaders or as guided exercise led by technicians, CSO workers, extensionists, scientists or government agents. It requires about an hour to be completed.

When a large number of cases are assessed using the CAET within a relatively homogeneous territory or spatial scale, and are shown to be fairly homogeneous in their variances, it may be desirable (or necessary in some cases) to draw upon a subsample of systems (or case studies) before proceeding with the performance criteria (Step 2). Selecting these case studies may be done by means of a typology. Step 1bis is proposed as an optional step that consists of analyzing and categorizing the individual farms/households. Criteria used can be location in the landscape, main orientation of production or any relevant criteria to the analysis. The results of the CAET can also be used to define the typology. Similar profiles of CAET scores over the 10 Elements can be aggregated in clusters. Farms/households can be clustered along a gradient of agroecological transition according to their aggregate CAET score over the 10 Elements.

TABLE 3 | Indices used for each of the 10 Elements of Agroecology.

Element	CAET indices
Diversity	• Crops • Animals, including fish and insects • Trees and other perennials • Diversity of activities, products and services
Synergies	• Crop-Livestock-Aquaculture integration • Soil-Plants management system • Integration with trees (agroforestry, silvopastoralism, agrosilvopastoralism) • Connectivity between elements of the agroecosystem and the landscape
Efficiency	• Use of external inputs • Management of soil fertility • Management of pests and diseases • Productivity and household's needs
Recycling	• Recycling of biomass and nutrients • Water saving • Management of seeds and breeds • Renewable energy use and production
Resilience	• Stability of income/production and capacity to recover from perturbations • Mechanisms to reduce vulnerability • Environmental resilience and capacity to adapt to climate change • Average diversity
Culture and food tradition	• Appropriate diet and nutrition awareness • Local or traditional identity awareness • Use of local varieties/breeds and traditional knowledge for food preparation
Co-creation and sharing of knowledge	• Platforms for the horizontal creation and transfer of knowledge and good practices • Access to agroecological knowledge and interest of producers in agroecology • Participation of producers in networks and grassroot organizations
Human and social values	• Women's empowerment • Labor (productive conditions, social inequalities) • Youth employment and emigration • Animal welfare (if applicable)
Circular and solidarity economy	• Products and services marketed locally (or in fair trade schemes) • Networks of producers, relationship with consumers and presence of intermediaries • Local food system
Responsible governance	• Producers' empowerment • Producers' organizations and associations • Participation of producers in governance of land and natural resources

Step 2—Core Criteria of Performance

Step 2 aims to document the multiple outcomes of agroecology, as opposed to the often singular focus in much of agricultural research (e.g., yields). It consists of assessing the performance of the farms/households on the five key dimensions identified as priorities for agriculture and food systems to achieve the Sustainable Development Goals (SDGs). The key dimensions were identified during the International Expert Workshop on Multidimensional Assessment of Agroecology (8th−9th October 2018, Rome). They correspond to the priority areas of work for policy makers.

Step 2, similarly to Step 1, was designed to be applicable and relevant to all contexts, agroecological zones and production systems. It should also be simple enough to use in a limited amount of time and with limited resources. The criteria used to assess the performance of systems should be able to generate harmonized data across countries, but should also be flexible enough to reflect specific characteristics and priorities in the local context. On the basis of the results of an on-line consultation and of the expert workshop and in order to comply with these requirements, a list of 10 core criteria was prioritized based on an initial list of almost 60 indicators. This list of 10 core criteria is presented in **Table 4**, as well as the proposed method for each of them and the main key dimension to which each contributes.

TABLE 4 | Ten Core criteria of performance of agroecology and their links to SDG indicators.

Main dimension	#	Core criteria of performance	Proposed method of assessment	Source
Governance	1	**Secure land tenure (or mobility for pastoralists)**	Type of tenure over land (or existence and use of pastoral agreements and mobility corridors)	SDG 1.4.2, 5.a.1 and 2.4.1 sub-indicator 11 FAO, 2018b
Economy	2	**Productivity**	Gross output value per hectare Gross output value per person	SDG 2.4.1 sub-indicator 1 FAO, 2018b
	3	**Income**	Revenue from plants, animals, other farm activities, subsidies, and rent of land - (operating expenses + depreciation + taxes + cost of labor + interests + costs for renting land) + subsidies	SDG 2.4.1 sub-indicator 2; Levard et al., 2019
	4	**Value added**	Gross value of agricultural production—(expenditures for inputs + intermediates consumptions + depreciation)	Levard et al., 2019
Health and nutrition	5	**Exposure to pesticides**	Quantity applied, area, toxicity and existence of risk mitigation equipment/practices, other ecosystem-based IPM strategies used, farm-derived products used	Sub-indicator seven of SDG 2.4.1 FAO, 2018b
	6	**Dietary diversity**	Minimum Dietary Diversity for Women, based on consumption of 10 food groups in the past 24 h	FAO and FHI 360, 2016
Society and Culture	7	**Women's empowerment**	Abbreviated Women's Empowerment in Agriculture Index (A-WEAI)	IFPRI, 2012
	8	**Youth employment opportunity**	Access to jobs, training and or education; migration	SDG 8.6.1 ILO., 2018
Environment	9	**Agricultural biodiversity**	Relative importance of crop varieties, animal breeds, trees and semi-natural environments in production units	SDG 2.4.1 sub-indicator 8.1, 8.6, 8.7 FAO, 2018b
	10	**Soil health**	SOCLA rapid and farmer friendly agroecological method to assess soil health, based on 10 indicators	Nicholls et al., 2004

In order to aggregate the results for all 10 core criteria, a traffic light approach similar to the one used in other assessment methods is recommended with three levels: unsustainable (red), acceptable (yellow), and desirable (green). A proposal for the interpretation of results and possible thresholds used to define the three levels for each criteria are provided in **Supplementary Information**.

Data collection for Step 2 should be conducted after Step 1 (CAET) or simultaneously if the enumerator is familiar with the questionnaire and can move easily between sections. Parts of the survey are conducted through interviews with the women in the household (women's empowerment) and some data are collected disaggregated by sex (land tenure, dietary diversity, youth employment). Another part of the survey is conducted as a transect walk on the farm and surroundings (agrobiodiversity), which can also help to inform the core criteria and ground-truth the collected data (e.g., exposure to pesticides, secure land tenure, soil health). Each criterion is presented in detail in the following sub-sections. The suggested protocols and complete questionnaire for data collection can be found in **Supplementary information**. Step 2 should take between 1 and 2 h to complete, depending on the size and complexity of the productive system.

The 10 core criteria do not aim at being exhaustive in assessing sustainability, for which more detailed and comprehensive frameworks already exist (cf. **Table 1**). Each criterion individually does not inform the whole dimension it addresses. Additionally, one criterion can address several dimensions. For example, secure land tenure is only one aspect of governance that can support more sustainable food and agriculture systems. Other aspects of governance include existing policies (addressed in Step 0), access to genetic diversity (addressed by core criteria "agricultural biodiversity" under the main dimension environment) or to water, among others. Additional or advanced criteria may be added to the list depending on the context of the evaluation, the question to be answered by the research and/or the availability of methods and data. These may include water use (e.g., FAO, 2019b), greenhouse gas emissions (e.g., FAO, 2016a,b), decent employment (e.g., FAO, 2015a), and resilience to climate change (FAO, 2015b), thereby offering the enumerator or conductor of the research the ability to dive deeper into additional criteria of interest and to look for relationships between agroecology and other key attributes of agricultural systems.

Secure Land Tenure (or Secure Mobility for Pastoralists)

Equitable access to land and natural resources is key to social justice and gender equality, but also to providing incentives for the long-term investments that are necessary to protect soil, biodiversity and ecosystem services and increase resilience to system stressors. Agroecology is tied to the concept of food sovereignty (Pimbert, 2018), especially when it has been found to have significant political implications (Méndez et al., 2013). It aims to make producers autonomous and self-sufficient, and to define their own models of development. Agroecology plays a central role in rural social movements, particularly in the context of land redistribution. Therefore, it can be expected that in regions where social movements are advocating for agroecology, the transition would be closely linked to a change in land tenure of farmers and/or secure mobility for pastoralists.

The criterion is based on the methodologies for SDG indicators 1.4.2, 2.4.1, and 5.a.1 (FAO, 2018b,c) which consider whether farmers have legal or secure claims to their land. It is completed with specific considerations for pastoralists, with data disaggregation for men and women. Specifically, it aims to measure legal and perceived rights to land by exploring the following aspects:

- Existence of legal recognition of access to land (mobility for pastoralists);
- Existence of formal document and presence of name on it;
- Perception of security of access to land; and
- Existence of the right to sell, bequeath, and inherit land.

Productivity

Measuring productivity provides information on the amount of resources necessary (i.e., production factors like land, capital and labor in classic economic terms, but also water or nutrients) to produce a given quantity or volume of product (Cochet, 2012; Sickles and Zelenyuk, 2019; Van der Ploeg et al., 2019). It is usually a measure of the relationship between the sum of all inputs and all outputs in physical terms (Timler et al., 2020). Improving the volume of production over time relative to the amount of inputs or resources used is an important aspect of performance. Improvements in agricultural productivity contribute to better food availability in a world with limited resources. They can also contribute to reduce environmental impacts of agriculture. While measuring productivity, it is important to consider the diversity of production systems and the need for accounting for all products and activities on farm.

The method proposed for measuring productivity with TAPE is the gross output value per hectare (based on SDG indicator 2.4.1 (FAO, 2018b) and in particular sub-Indicator 1) and the gross output value per person working within the productive system, in order to better account for productivity in extensive and often mobile systems such as pastoralism. This criterion therefore also informs SDG indicator 2.3.1 (Production per unit labor). The farm output corresponds to the total volume of agricultural output at farm level (crops, animals, trees, and animal products). Since the volume of agricultural outputs is not measured in commensurate units (e.g., not all outputs are measured in tons, and tons of different outputs represent different products), outputs are converted to monetary terms by multiplying them with the prices at the gate in local currency and converted to purchasing power parity (OECD, 2019). Alternatively, when dealing with farming systems specialized in food production, all outputs may be expressed as calories or grain equivalents or nutritional carrying capacity (number of people that can be fed per hectare with the available nutrient considered) (e.g., Timler et al., 2020). The farm agricultural land area is defined as the area of land used for agriculture within the farm (FAO and UNSD, 2012). The number of persons working on the farm is the total number of working persons, including family and paid labor, in full time equivalents.

Income

An important part of sustainability in agriculture is the economic viability of the system. This is driven to a large extent by profitability and the net income that the producer/household is able to earn from agricultural operations relative to the investment in land, labor and other assets. The profitability of the production system is one of the key measures on which many decisions are based and is considered a driver of agricultural policies.

Improving producers' efficiency through the enhancement of biological processes and reduction of costs from external inputs can increase net income of producers and create more inclusive and innovative markets that reconnect producers and consumers in a circular and solidarity economy (Van der Ploeg et al., 2019). For example, adopting agroecological practices increased farm profitability in 66 percent of cases analyzed by D'Annolfo et al. (2017).

The method proposed is based on SDG indicator 2.4.1 (FAO, 2018c), and in particular the sub-Indicator 2 (Farm net income), and for SDG 2.3.2 (income of small-scale food producers) (FAO, 2019c) and on the evaluation of economic performance from Levard et al. (2019). The family net agricultural income is calculated as follow:

Revenue from agricultural activities (quantity of crops, animals, animal products, and other activities sold multiplied by the price at the gate for these items):

+ Subsidies
- Cost of inputs (seeds, fertilizers, pesticides, breeding stock, feed, veterinary products and services, energy)
- Taxes, cost of hired labor, interest on loans, cost of renting land and depreciation of machinery and equipment over time

In this way, income is not a reflection of monetary availability only, because food that is produced and consumed by the household is also included. Similarly, special attention should be put on the value of inputs provided by the household, considering their opportunity cost. Moreover, a separated analysis should be done for the subsidies in order to analyze their relative importance in the total income of the family. The results should be converted into purchasing power parity (OECD, 2019).

Value Added

While income is a basic indicator of how a system performs economically, it does not provide sufficient information on how a production system creates value for producers. As explained by Van der Ploeg et al. (2019), value added is a central concept in agroecology because it contributes to income and is considered to be the gross value of production minus the costs of production. Agroecological producers seek to maximize the ratio between the value added and the gross value of production, rather than just trying to increase the gross value of production. From such a starting point, the logical guiding principle of conventional farming is to increase the total production realized per unit labor, which, in practice, translates into ongoing scale-enlargement and/or reducing labor input. On the contrary, agroecological farms tend to be more diversified than conventional ones, make labor in farming central, try to enhance as much as possible the quality of internally available resources, and seek the balance between these and external inputs. Therefore, they tend to show higher levels of net added value.

The net value added of a productive system represents the creation of wealth obtained through the system itself (Levard et al., 2019). It is calculated by subtracting all the expenditures for inputs, the intermediate consumption, and the depreciation of machines and equipment from the gross value of the agricultural production. It excludes subsidies and does not deduct expenses related to taxes, hired labor and renting land or interests on loans, which makes it a distinct criterion from income. For example, producers in situations of high debts may have a low income because of high interest they have to pay every year but they may still generate important added value from their system. It is calculated as follow:

Gross output value of the agricultural production

- Cost of inputs (seeds, fertilizers, pesticides, breeding stock, feed, veterinary products and services, energy)
- Depreciation of machinery and equipment over time.

Exposure to Pesticides

Synthetic pesticides are extensively used in crop production to control harmful pests and prevent crop yield losses or product damage. Because of negative biological activity and, in certain cases, long persistence in the environment, synthetic pesticides can cause undesirable effects to human health and to the environment - soil, water, flora and fauna (World Health Organization, 2020). Producers and agricultural workers can be routinely exposed to high levels of pesticides, at usually a much greater rate than consumers (Praneetvatakul et al., 2013; Lekei et al., 2014; Gangemi et al., 2016). Producers' exposure mainly occurs during the preparation and application of the pesticide and during the cleaning-up of application equipment. Producers who mix, load, and apply pesticides can be exposed to these chemicals due to spills and splashes, direct contact as a result of faulty or missing protective equipment, or even drift. However, producers can be exposed to pesticides even when performing activities not directly related to pesticide use, e.g., producers who perform manual labor in areas treated with pesticides can face major exposure from direct spray, drift from neighboring fields, or by contact with pesticide residues on the crop or soil. This kind of exposure is often underestimated.

Producers' exposure to pesticides can be reduced through the elimination of the use of Highly Hazardous Pesticides (World Health Organization, 2010) and the correct use of the appropriate type of personal protective equipment in all stages of handling regulated pesticides and, overall, through reduced use of pesticides. Both men and women should be provided with this information and with the appropriate equipment and measures to reduce risks to their health (Waichman et al., 2007). Agroecology promotes different measures to reduce pesticide use, such as biological control, the integrated management of pests based on ecosystem approaches, the use of cover crops to reduce weed infestation, the integration of animals to remove weeds and/or pests etc. A fundamental measure of the benefits of agroecology is therefore the degree to which it reduces the use of harmful, and often costly, pesticides.

The proposed method is based on the sub-indicator 7 of SDG 2.4.1 (management of pesticides) (FAO, 2018b), and more specifically on the quantity of bio-pesticides and synthetic pesticides applied, their level of toxicity (highly/moderately/slightly, according to Damalas and Koutroubas, 2016) and the existence of mitigation techniques (e.g., use of protection before and after spraying, signaling the sprayed areas) when applying the pesticides and for other people living and working around the interested area (Ross et al., 2015). The implementation of practices for the ecological management of pests that can substantially reduce the need of chemicals are also incorporated (PAN, 2015). More specifically, the recommended desirable score for this criteria corresponds to using organic pesticides and not using highly and moderately toxic synthetic pesticides, while using at least 4 mitigation techniques if synthetic fertilizers of low toxicity are used (see **Supplementary information**).

Dietary Diversity

Today, there are still gaps in nutrient supply in some regions of the world, especially for nutrient-dense food groups (Herrero et al., 2017). To address the imbalances in our food systems and move toward a zero-hunger world addressing all forms of malnutrition (hunger, micro-nutrient deficiencies and obesity), increasing production alone is not sufficient. Re-balancing food habits, promoting diverse and healthy food production and consumption, and supporting the right to adequate food are all elements of an agroecological transition (FAO, 2018a). For example, species richness on farm, one measure of biodiversity, has been found to be highly correlated with micronutrient adequacy in human diets (Lachat et al., 2018).

Obtaining detailed data on household food access or individual dietary intake can be time consuming and expensive. It requires a high level of technical skill both in data collection and analysis. Dietary diversity is a qualitative measure of food consumption that reflects household access to a variety of foods and is also a proxy for nutrient adequacy of the diet of individuals.

The index proposed for TAPE is the Minimum Dietary Diversity for Women (FAO and FHI 360, 2016). Because women often prioritize the nutrition of other family members, especially children, and there is evidence showing the association between maternal and child diversity (Nguyen et al., 2013), they can be considered as a proxy for the nutritional status of individuals within the household.

The dietary diversity score consists of a simple count of how many food groups were included in the food consumed over the preceding 24 h. Foods are grouped in the following 10 groups: grains, white roots, tubers, and plantains; pulses (beans, peas, and lentils); nuts and seeds; milk and dairy products; meat (red), poultry, fish; eggs; dark green leafy vegetables; other vitamin A-rich fruits and vegetables; other vegetables; other fruits. These groups are standardized and are of universal applicability; as such they are not culture-, population-, or location-specific and can be collected in a gender-disaggregated manner in a short amount of time.

Women's Empowerment

Women contribute ∼43% of all agricultural labor in low and middle-income countries (FAO and ADB, 2013). They also play a vital role in household food security, dietary diversity and health, as well as in the conservation and sustainable use of biological diversity (especially in regard to conservation and management of seeds, in building resilient livelihoods and in transforming food systems. But in spite of this, they face persistent obstacles, economic constraints, and remain economically marginalized and vulnerable to violations of their rights, while their contributions often remain unrecognized. For example, in a study by Smith and Haddad (2015), food quantity only accounted for an estimated 18% of reduced stunting, food quality contributed 15% and women's education contributed 22% to the total reduction in stunting.

Women tend to have poorer access to productive assets, such as land, capital, inputs, technology, information and services. Therefore, their decision-making capacity remains limited, including in community decisions over natural resources. For example, in sub-Saharan Africa, agricultural productivity levels of female farmers are between 20 and 30% lower than those of male farmers, because of the gender gap in access to resources (FAO, 2011). Gender inequity in Malawi, for example is persistent in terms of access to extension, land and credit, despite women making up a significant proportion of the agricultural labor (Place and Otsuka, 2001; Farnworth and Colverson, 2016; Deininger et al., 2017). Globally, rural women experience poverty and exclusion disproportionately, and fare worse than rural men as well as urban women and men on every gender-sensitive indicator for which data are available. Women and girls also face a higher risk of undernourishment (FAO, 2020). Addressing pervasive gender inequality will generate multiple benefits in terms of food security and poverty alleviation, especially for the family unit (FAO, 2017a).

Through agroecological approaches, women can develop higher levels of autonomy by building knowledge, through collective action and creating opportunities for commercialization, and enhancing their negotiation and leadership skills (Oliver, 2016; Kerr et al., 2019b; Michalscheck et al., 2020). Opening spaces for women and girls to become more autonomous can empower them at household, community levels and beyond —for instance, through participation in producer groups, and increasing their access to agricultural services and rural institutions (FAO, 2018a).

The Women's Empowerment in Agriculture Index (WEAI) is a survey-based index designed to measure the empowerment, agency, and inclusion of women in the agricultural sector (IFPRI, 2012). The WEAI has been used extensively since 2012 by a variety of organizations to assess the state of empowerment and gender parity in agriculture, to identify key areas in which empowerment needs to be strengthened, and to track progress over time. The methodology proposed for TAPE is an adaptation of the Abbreviated version of the Women's Empowerment in Agriculture Index (A-WEAI) (IFPRI, 2015), which measures the roles and extent of women's engagement in the agriculture sector in five domains of empowerment: (1) decisions about agricultural production, (2) access to and decision making power over productive resources, (3) control over use of income, (4) leadership in the community, and (5) time use. The questionnaires is completed with the main female in the household and it also measures women's empowerment relative to men within their households, by providing answers to questions about decision making or asset management such as "Myself or both my husband and I" or "My husband or someone else."

Youth Employment Opportunities

In many countries, rural youth face a crisis of employment. Globally, some 620 million young people are neither working nor studying, and 1.5 billion are working in agriculture and in self-employment (World Bank, 2013). About 37% of migrants are below 30 years old (UNDESA, 2019). High rates of unemployment and underemployment are among the root causes of distress out-migration from rural areas (FAO, 2016c). In Africa, 325 million young people (from 15 to 24 years old) will be looking for jobs by 2050 (Christiaensen, 2020).

Approaches to agriculture that are based on knowledge and skilled labor, such as agroecology, can provide a promising solution as a source of decent jobs, by offering rural employment and opportunities that meet the aspirations of rural youth and contribute to decent work (FAO, 2018a). For example, Dorin (2017) showed that innovations requiring investments that save labor may not be seen as desirable where labor is more readily available than monetary resources, making labor-saving technologies less advantageous.

A common indicator for measuring the creation of decent jobs for youth in rural areas has not been established yet. The method proposed for TAPE is an index similar to SDG indicator 8.6.1 (ILO., 2018) and based on the proportion of youth (aged 15–24 years) in the household enrolled in education, employment or training and the proportion of young people who have migrated or that wish to migrate. To the extent possible, the collection of this data should be sex-disaggregated to better highlight the differences between boys and girls of different ages (e.g., Michalscheck et al., 2018). Scores and weights to aggregate all indicators into one score are provided in **Supplementary information.**

Agricultural Biodiversity

Biodiversity for food and agriculture includes the domesticated plants and animals raised in crop, livestock, forest and aquaculture systems, harvested forest and aquatic species, the wild relatives of domesticated species, other wild species harvested for food and other products, and what is known as "associated biodiversity," the vast range of organisms that live in and around food and agricultural production systems, sustaining them and contributing to their output (FAO, 2019d). Meeting the challenges of climate change, improving nutrition and health, and achieving a transformation toward more sustainable and equitable production systems all require the conservation of agricultural biodiversity.

Areas of the world with higher agricultural diversity produce more nutrients (Herrero et al., 2017). Very small, small and medium-sized farms, found mostly in traditional and mixed production systems, produce more food and nutrients in the most populous (and food insecure) regions of the world than large farms in modern food systems (Pengue and Gemmill-Herren, 2018). In addition, 5 billion people are estimated to live in traditional and mixed food systems relying on a diversity of plants, animals and activities, which is about 70% of the world's population (Ericksen, 2008; UNEP, 2016; HLPE, 2017; Pengue and Gemmill-Herren, 2018). Numerous studies have found a positive relationship between diversified farming systems and human nutritional outcomes for smallholder farms (Jones et al., 2014; Powell et al., 2015; Bellon et al., 2016; Demeke et al., 2017). Mixed crop-livestock farming systems that occur in all agro-ecological zones, are estimated to cover 2.5 billion hectares globally, and to produce 90% of the world's milk supply and 80% of the meat from ruminants (Herrero et al., 2013).

Various elaborated methods to assess agricultural biodiversity were developed in different contexts (Teillard et al., 2016; Leyva and Lores, 2018; PAR, 2018; BI, 2019). The proposed methodology follows the approach of sub indicator 8.1, 8.6, and 8.7 of SDG indicator 2.4.1 (FAO, 2018b, which rely on an inventory of all species, varieties, and breeds used. The proposed methodology corresponds to a composite indicator taking into account the diversity of species, varieties and breeds and their relative importance. It is based on a Gini-Simpson index of diversity for crops (including cultivated trees) and animals, and on an index assessing the presence of natural vegetation, trees, pollinators, and other beneficial animals. The data are collected during a transect walk on the farm during the survey. The Gini-Simpson index of diversity is calculated with the following formula:

$$1 - D = 1 - \Sigma\, p_i^2$$

in which p_i is the relative importance of each variety or breed used for production (also called abundance) and i the proportion of agricultural land (or number of animals) found in the ith species. D is subtracted to 1 in order to have 100% as the highest diversity score and 0 as the lowest.

More information on how to calculate the proportions of each crop variety and livestock breed, and how to include pollinators and natural vegetation is available in the **Supplementary Information**.

Soil Health

Soil underpins agricultural output and ecosystem functioning. Sustaining the quantity and quality of organic matter in agricultural soils is a key element of sustainability in agriculture (FAO, 2017b). Soil health includes the stabilization of soil structure, the maintenance of soil life and biodiversity, retention and release of plant nutrients and maintenance of water-holding capacity, thus making it a key criterion not only for agricultural productivity but also for environmental resilience (FAO, 2005).

A number of practices used in agroecological systems can contribute to improving soil health, for example, minimal mechanical soil disturbance, organic fertilization from animal manure or compost, permanent soil cover (organic matter supply and thus increase in water retention capacity through the preservation of crop residues and cover crops or animal manure), crop rotation for biocontrol and efficient use of the soil profile, rotational grazing management, and minimal soil compaction.

Several methodologies for assessing soil health have been developed, some more sophisticated (e.g., Pheap et al., 2019; Thoumazeau et al., 2019), and others more farmer friendly (UTT, 2014; MAONIC, 2019). The method proposed was developed in Nicholls et al. (2004) and then disseminated by the Sociedad Científica Latinoamericana de Agroecología (SOCLA). The 10 proposed soil health indicators can be applied and interpreted jointly by farmers and researchers. The method is conducted at the same time as the transect walk for assessing agricultural biodiversity. The SOCLA 10 indicators of soil health are: soil structure; degree of compaction; soil depth; status of residues; color, odor, and organic matter; water retention; soil cover; signs of soil erosion; presence of invertebrates; and microbiological activity.

Each indicator is valued separately, and a value is assigned between 1 and 5, according to the attributes observed in the soil (one being the least desirable value, three a moderate or threshold value and 5 the most preferred value). Every indicator is provided with a description for supporting the evaluator. For instance, in the case of the indicator of soil structure, a value of 1 is given to a "dusty soil, without visible aggregates," a value of 3 to a "soil with some granular structure whose aggregates are easily broken under soft finger pressure," and a value of 5 to a "well-structured soil whose aggregates maintain a fixed shape even after exerting soft pressure." The details of the descriptions of the 10 indicators are provided in **Supplementary Information**. Once all soil indicators are assessed, individual indicators can be presented in a radar type graph or an average score of soil health can be calculated.

Step 3—Participatory Analysis of Results

The diagnostic based on the 10 Elements of agroecology (Step 1) and the analysis of performance based on the core criteria (Step 2) are used to reveal the strengths and weaknesses of the systems assessed and to explain their performance in the context of the enabling environment from Step 0. For example, a system with high synergies between plants and animals and high levels of recycling in Step 1 may still perform poorly in terms of income (Step 2) if it has limited access to markets (Step 1 "Circular and solidarity economy" and Step 0).

Step 3 should be conducted in a participatory manner with the community or territory identified in Step 0 and in which the farm surveys were conducted in order to (1) verify the adequacy and performance of the framework; (2) confirm/interpret the analysis to make it context-relevant (including the sampling and up-scaling from farm to territory and to adjust the thresholds used on Step 2 for the traffic light approach); and (3) design/discuss possible ways forward to enhance the enabling environment and support the transition, potentially utilizing the tool to monitor progress. This step can also include the following points to contextualize the interpretation of results:

- The review of CAET results (Step 1) and a proposal for weighting the various indices within each element to emphasize critical aspects in the analysis to ensure contextualized relevance;
- The review of the performance criteria results (Step 2) and a review of the thresholds applied to each of the criteria for the "traffic light" approach;
- The review of the aggregation of farm/production unit level results for an analysis at territorial level as well as of the sampling method chosen.

PRELIMINARY RESULTS

TAPE is being piloted in several geographic regions and production systems in order to assess its relevance and validate the underlying methodological choices. Further data consolidation and data collection to populate the global database are needed but several conclusions can already be drawn from these pilot studies. Here we take some of these ongoing efforts in the field to illustrate two possible applications of TAPE: (1) assessing the degree of agroecological transition in a given territory (for example to assess the impact of a policy or a project) and (2) evaluating the multi-dimensional performance of agroecological farms (e.g., to compare farming systems across regions or territories). These two types of application are not exhaustive. TAPE can be applied to reach different objectives, including, for example, for project formulation or corporate assessments in private companies, and more results will be available as pilots are completed. More lessons learnt will also be available after completion of Step 3 (participatory validation of results), as well as more insights on possible weightings of elements and indices in Step 1 and thresholds for the traffic light approach in Step 2.

Assessing Agroecological Transitions

Figure 3A shows the application of the Step 1 of TAPE to assess the degree of agroecological transition in a family farm in Cuba, comparing three stages: conventional monoculture of tobacco; intermediate transition status with increased diversity in production, synergies within the agroecosystem and use of self-produced inputs; and the last stage of this transition. Results presented in Lucantoni (2020) show that the transition, supported by a specific public policy, had positive impacts on food security, income, biodiversity, soil health, youth employment, and exposure to pesticides.

Figure 3B shows the application of Step 1 of TAPE to a smallholder farm in Central Angola, before and after the implementation of a 4-year project aimed to improve producers' livelihoods and nutrition by reducing dependence on synthetic fertilizers, improving soil health and reintroducing animals in the agroecosystem. The CAET spider charts show that average scores for the 10 Elements have all improved, ranging between 10 and 30% before the project and between 30 and 50% after the project. This illustrates how TAPE can be used for project monitoring and evaluation.

Results from the application of Step 1 and 1bis (typology) in 25 farms in Patagonia (Argentina) show that mixed crop-livestock systems have a higher level of diversity, synergies and resilience (**Figure 3C**). Mixed and crop production systems score better in terms of circular and solidarity economy due to better connection with short value chains. Farms specialized in livestock production show higher average scores in recycling but lower in co-creation and sharing of knowledge, because these systems are normally situated further from urban areas, with less organizations for local support and hence limited access to new agroecological knowledge (Álvarez et al., 2019; De Pascuale Bovi et al., 2019). Almost all the farms were already engaged in an agroecological transition even though the environment was not favorable. These results showed the role of local cultural heritage and traditional management practices for agroecological transitions, especially in the absence of specific support for agroecology.

Evaluating the Multi-Dimensional Performance of Agroecological Farms

Steps 1 and 2 were applied to an integrated farm in Thailand. Results in **Figure 4** show that the high level of diversity (rice, vegetables and fish production as well as its activity as a training center), together with the relatively high score in circular economy (e.g., products sold directly to neighboring households through social media), explain the high level of productivity but also of income and added value compared to the country average. However, limited synergies and recycling were found between the different sub-systems, which explains the relatively low score in agricultural biodiversity (significant share of the farmland is in rice monocropping) as well as the high exposure to pesticides.

Steps 1 and 2 were also applied to 228 farms in Cambodia. Preliminary results show that higher average scores in Step 1 (CAET) are linked to more positive results from Step 2 (**Figure 5A**). Step 2 results are presented using the traffic light approach where green scores +1, red −1 and yellow 0, for a total ranging from 10 to −10 (y axis). **Figure 5B** shows that productivity per hectare and per person seems to be higher for farms with higher scores in Step 1 (i.e., those that are further in their transition to agroecology based on the 10 elements). **Figure 5C** shows the same trend for agrobiodiversity. Such results illustrate the strong coherence between the two steps of the method and the coherence of the 10 Elements of agroecology in order to achieve a sustainable production. Logical links between the 10 elements of Step 1 and the 10 criteria of Step 2 also contribute to explain these results. Deeper analysis as recommended for Step 3 (participatory interpretation of results) is needed to clarify.

DISCUSSION

Building on existing indicators and sustainability evaluation frameworks, and capitalizing on the experience of a vast network of participating organizations worldwide, the Tool for Agroecological Performance Evaluation (TAPE) is presented as a simple, operable, yet comprehensive quali-quantitaive approach

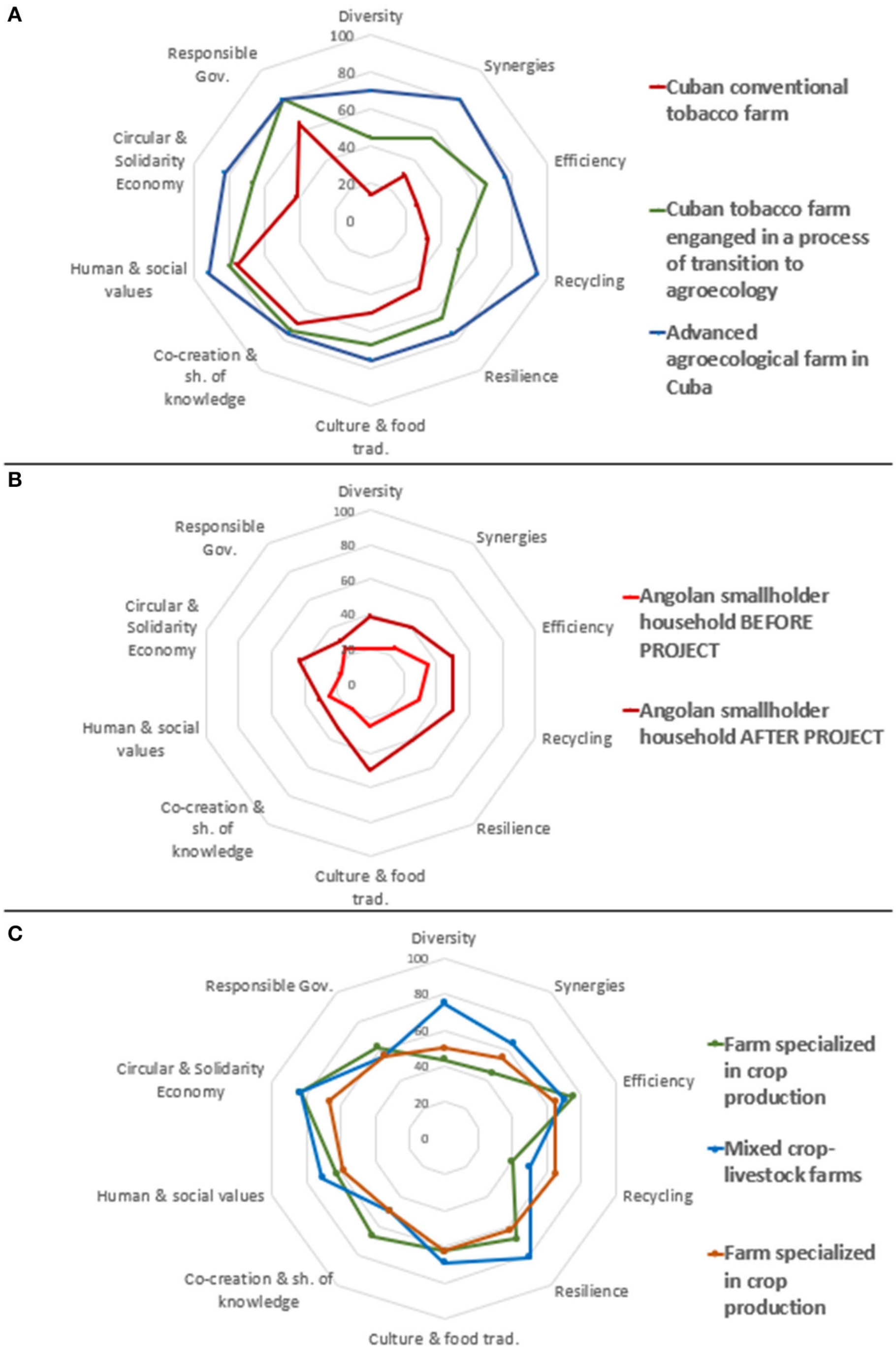
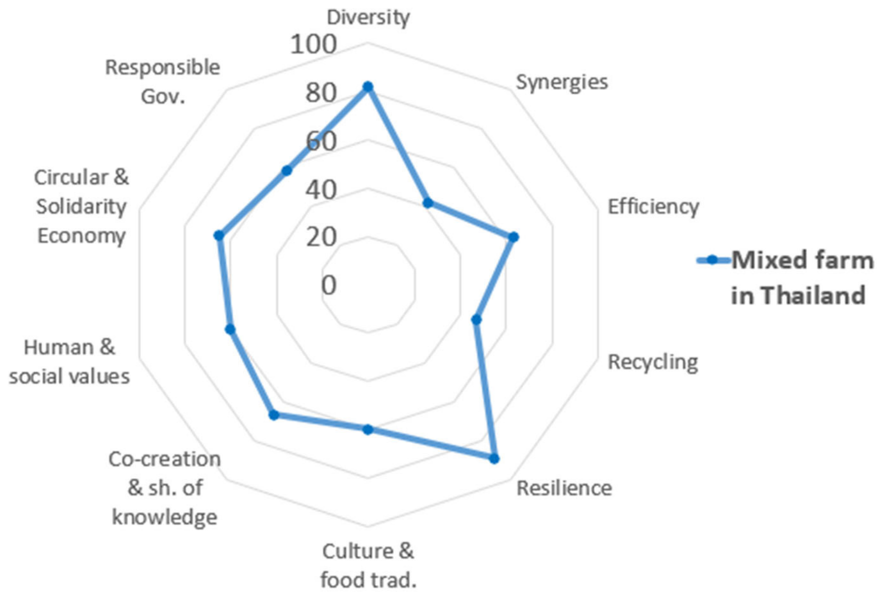


FIGURE 3 | Results of the CAET (Step 1) from **(A)** a family farm in western Cuba at different stages transitioning to agroecology (Lucantoni, 2020); **(B)** a smallholder farm of Central Angola, before and after a project for sustainable rural development and improved nutrition and **(C)** 25 farms in Patagonia (Argentina) after using the Step 1-bis Transition Typology (Álvarez et al., 2019).

to assess the degree of transition of farms and communities to agroecology, and measure their impact on key attributes of systems necessary to the achievement of the UN Sustainable Development Goals (SDGs): a healthy environment, people's health and nutrition, societal and cultural values, economic development and sound governance systems.

The application of TAPE will generate harmonized and global evidence, whether from new data collection or from existing datasets revisited with or completed for TAPE. This global database, available on a United Nations server, will be used by FAO and partners to develop a number of studies and recommendations for policy makers at various scales of



Core criteria of performance	Results	Traffic light approach
Secure land tenure	No document but perception of secure land tenure	Acceptable
Productivity	USD 9,460/ha/year (Thailand average: 1,678) USD 10,915/FWU/year (Thailand average: 3204)	Positive
Income	USD 9,460/FWU/year (Thailand average: 3204)	Positive
Value added	USD 6744/ha/year (Thailand average: 2036)	Positive
Exposure to pesticides	Use of pesticides of class II (moderately toxic) with less than 4 mitigation strategies	Unsustainable
Dietary diversity	Minimun Ditary Diversity for Women 8/10	Positive
Women's empowerment	A-WEAI score 0.849	Positive
Youth employment	No young people in the household	N/A
Agricultural biodiversity	Gini-Simpson index 54.7%	Acceptable
Soil health	data not collected	N/A

FIGURE 4 | Results of Step 1 and Step 2 applied to a farm in Thailand.

aggregation. The intention is to further this research agenda by beginning to provide data on (i) the characterization of agroecological transitions (CAET, Step 1) and (ii) the contribution of such transitioning farms to more sustainable food and agriculture systems (Step 2) and being able to connect these data with inferences about the enabling contextual environment defined in Step 0. This will allow addressing questions such as how many farms are engaged in an agroecological transition; how far have they progressed in the transition; what are the combinations of practices that are most common; are there regional, territorial clusters that can be linked to economic, social and environmental impacts at national and regional scales?—all relevant questions for baseline characterization and monitoring and evaluation of the impact of national or regional policies designed to enable agroecological transitions. The geospatial data that is collected through TAPE could be linked to existing national and international datasets and eventually be integrated into participatory foresight models (Cradock-Henry et al., 2020)

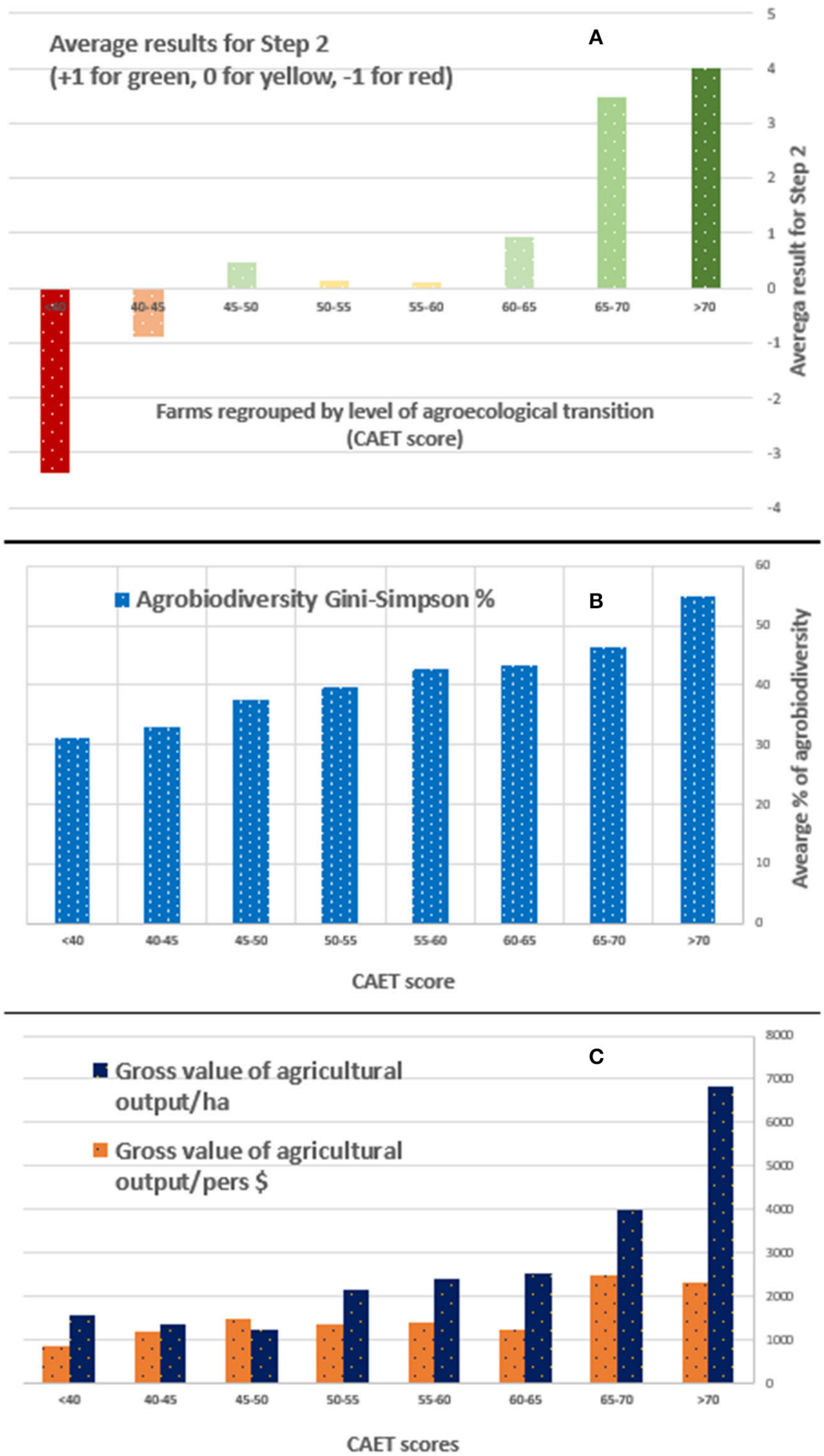


FIGURE 5 | TAPE results from 228 farms in Cambodia. **(A)** Average score from the traffic light approach (Step 2) per quintiles of CAET (Step 1). **(B)** Average Gini-Simpson index for agricultural biodiversity (Step 2) per CAET quintiles (Step 1). **(C)** Average gross value of production per hectare and per person (from Step 2) by CAET quintiles (Step 1).

that are increasingly being used for policy making. The original contribution of TAPE in this regard is that it can be applied to all types of production systems and territories, which means that through progressive data collection, we will begin to be able to visualize these transitions as they unfold over time and help direct producers and policy makers toward sustainability.

Measuring the sustainability of agriculture has long been a research question -as well as one of overall sustainable development. During the eighties and nineties, there was a multiplication of tools based first on individual indicators and later on indexes aggregating several indicators, which were used to score the systems assessed (De Olde et al., 2016; Migliorini et al., 2018). With the recognition of the value of citizen-science in transitions to sustainability (Sauermann et al., 2020), more recent efforts have focused on developing approaches that could guide a process of co-development and participatory evaluation. This means offering users a structured approach to define meaningful indicators along the entire process of evaluation, from design to the organization of data and interpretation (Cândido et al., 2015). MESMIS is an example of such a framework (**Table 1**) where the properties of the system or the system attributes can be mobilized by users to define criteria and indicators in a structured way. Indicator frameworks that examine resilience between farming systems, including agroecological ones, have been developed and applied in different contexts (e.g., Jacobi et al., 2018), but they do not consider the transition process as such. In the last years, methods and concepts to specifically study agroecological transitions have been developed borrowing from sustainability transition theory (Anderson et al., 2019), considering 'performance' indicators (e.g., Trabelsi et al., 2016), the dynamics of famers' networks (Teixeira et al., 2018) or merging these with complex adaptive systems and state and transition theories (Tittonell, 2020). TAPE proposes a synthesis of these approaches and concepts.

TAPE is also inspired by the MESMIS approach in the sense of using system properties (i.e., the 10 Elements of Agroecology, five SDGs dimensions) to develop evaluation criteria, but aims to take this approach one step further by encouraging harmonization at the criteria level, monitoring of real-life transitions over time, and creating inter site comparisons by building public global databases. TAPE is therefore simplified in terms of the number of criteria considered and is more prescriptive than tools that are designed purely for research purposes yet flexible in terms of indices and scores, in order to be of relevance for development actors and policy makers. While frameworks such as MESMIS that leave the selection of indicators solely to the user are very useful to support local decision-making processes, their results can often not be comparable given the highly contextualized results that they produce. One of the motivations for the development of TAPE has been to generate harmonized and consistent evidence at the global level, which requires some level of prescription and systematization. The first field applications of TAPE show that the tool is well-received by CSOs and agricultural extension agents, who have been able to adapt it to their situations without losing the overall comparability. These experiences also report that the participatory approach also contributed to the emergence of new research questions and collaborations with farmers (e.g., Álvarez et al., 2019; De Pascuale Bovi et al., 2019). First results show that there is a strong coherence between the two main core steps of TAPE, the first one aiming at characterizing the agroecological transition and the second one aiming at characterizing some of the performances and impacts of such systems. While the information collected for Step 1 (CAET) and Step 2 (core criteria of performance) may be perceived as partially redundant for some indices/criteria, the treatment of this information and the purpose of each step are actually complementary: Step 1 informs about how far the system has progressed in its agroecological transition, contributing to better describe and define agroecology globally in a diversity of contexts, while Step 2 provides an assessment of the system's impact in quantitative terms, and therefore how its performance links to its degree of transition. The complementarity of the two steps may provide farmers and local actors with a useful information to assess and pilot their own transition and developing sustainable agroecological systems.

Despite the large promise of TAPE, there are a number limitations in its current form that have been identified through the piloting process. First, the core criteria of TAPE and the selected methods to assess them may seem to be more directly applicable to family farming than to large scale commercial/industrial farming (e.g., nutritional diversity, youth employment). However, TAPE can support agroecological transitions in all forms of production. Its application to large scale farmers, including in the case of cooperatives and corporate farming, requires some adaptation, which will need more pilot testing, and it can help identify how these systems can better contribute to nutritional diversity or youth employment, for example. Second, TAPE requires a translation into local contexts and languages: while it has global relevance, the pilot tests show that its application requires a translation of the questionnaires to include local characteristics of agroecosystems and socio-economic contexts (e.g., soil health indicators, food groups for the nutritional diversity). The status of local populations in terms of food security could also be a critical element of context for the assessment, in addition, and as a preamble, to nutritional diversity (e.g., Timler et al., 2020). This preliminary step that has already been identified in several assessment frameworks. In addition, adequate capacity development is required for local partners to apply and use TAPE in their work and share the information, promoting horizontal relationships between people applying the framework and contributing to a community of practice.

TAPE is being piloted in different contexts and by different partners. Lessons learnt from these experiences will contribute to its development and the participatory learning approach adopted for the design of TAPE will continue so that the final guidelines will be robust and more widely applicable. Plans for the further development of the approach will include, for example, how to better address the territorial level. Some dimensions that are evaluated are also relevant at higher scales than the farm/household level (e.g., Novotny et al., 2020). This is the case for example for nutrition, which is assessed in agricultural households only and not across the supply chains that structure food systems (Fanzo et al., 2020; Vonthron et al., 2020). Youth employment is another example where non-agricultural job opportunities are considered, but not analyzed at the relevant scale of the territory (Losch, 2016). The creation of territorially appropriate criteria and indicators, in lieu of simple aggregation, will shift the frame of thinking from individual farms/households to more collective strategies that can ensure broader social, environmental and economic benefits. In this development process, it will be important to ensure at the same time that (i) the method and indicators (including potential advanced ones) suit the goals of the specific assessments and (ii) TAPE remains sufficiently harmonized to allow consolidation and comparison at the global scale.

CONCLUSION

The recent report from the UN Committee for Food Security called upon more rigorous and consistent evaluation of agroecology, including shared performance indicators that assessed a broader range of dimensions beyond productivity (HLPE, 2019). TAPE is a first step based on collective efforts at international level to address this knowledge gap.

Building upon various existing assessment frameworks, TAPE is proposed as a comprehensive tool to assess the multi-dimensional performances of agroecosystems across different aspects of sustainability and to support a transition toward more sustainable food systems. It was designed to remain simple and to require minimum training and data collection.

The process that led to the development of TAPE included the horizontal participation of a large diversity of worldwide stakeholders, who shared their interests in assessing the extent of agroecological transition, monitor progress on the various dimensions of sustainability, and compare the performance of agroecosystems around the world. TAPE has hence a global relevance and can be applied to all types of production systems, to generate information relevant to policy makers, scientists, CSOs, international organizations, the private sector and producers. It is at the same time broad in the number of dimensions of sustainability covered and simple in its application. It can be used to support the re-orientation of public investment toward more sustainable agriculture and food systems.

This tool can also provide a framework for governments and public actors for the adaptation and re-design of research and development programmes and the evaluation of policies, as well as rural advisory services and extension programmes to properly address sustainable agriculture in the context of the SDGs. Indeed, the information collected by TAPE can be used to inform various SDG indicators, including 2.4.1 (sustainable agriculture), 1.4.2 (land rights) or 8.6.1 (biodiversity).

More specifically, TAPE can help farmer, but also governments, extension services and scientist, identify strengths and weaknesses of productive systems and food systems. By providing a diagnostic of the agroecological elements that are (or are not) implemented within the farm, Step1 can support the adoption of practices that contribute to these elements (e.g., for more diversity or more co-creation of knowledge). Moreover, the application of TAPE itself can help support the co-creation and sharing of knowledge and spread agroecological practices at community level. Consultations between (local) experts and producers often follow a top-down approach, while TAPE can be used as a peer-to-peer tool to identify and prioritize actions. Finally, the tool makes an overall assessment of a system through a simple survey and gives immediate and quantifiable results in a short amount of time, which is valuable for all actors in food systems.

FAO is currently working with partners in more than 10 countries for piloting TAPE and is inviting more partners to engage in this piloting phase.

DATA AVAILABILITY STATEMENT

The datasets generated for this article are not readily available because of confidentiality of data collected at farm level. Only aggregated results are available. Requests to access the datasets should be directed to anne.mottet@fao.org.

AUTHOR'S NOTE

All authors were part of the core development team of the tool or members of the Technical Working Group formed to support the development. They all contributed with inputs to the text.

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

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2020.579154/full#supplementary-material

REFERENCES

Altieri, M. A. (2002). Agroecology: the science of natural resource management for poor farmers in marginal environments. *Agric. Ecosyst. Environ*. 93, 1–24. doi: 10.1016/S0167-8809(02)00085-3

Altieri, M. A. (2018). *Agroecology: The Science of Sustainable Agriculture*. Boca Raton, FL: CRC Press. doi: 10.1201/9780429495465

Álvarez, V., De Pascuale, J., Hara, S., Cardozo, A., Ocariz, P., Furlan, N., et al. (2019). "Evaluación Multidimensional de la Agroecología," in *Sistemas Agropecuarios de Patagonia Norte. Primer Congreso Argentino De Agroecología*. Mendoza: Universidad Nacional de Cuyo, 425–429.

Anderson, C. R., Maughan, C., and Pimbert, M. P. (2019). Transformative agroecology learning in Europe: building consciousness, skills and collective capacity for food sovereignty. *Agric. Hum. Values* 36, 531–547. doi: 10.1007/s10460-018-9894-0

Barrios, E., Gemmill-Herren, B., Bicksler, A., Siliprandi, E., Brathwaite, R., Moller, S., et al. (2020). The 10 elements of agroecology: enabling transitions towards sustainable agriculture and food systems through visual narratives. *Ecosyst. People* 16, 230–247. doi: 10.1080/26395916.2020.1808705

Bellon, M. R., Ntandou-Bouzitou, G. D., and Caracciolo, F. (2016). On-farm diversity and market participation are positively associated with dietary diversity of rural mothers in southern Benin, West Africa. *PLoS ONE* 11:e0162535. doi: 10.1371/journal.pone.0162535

BI. (2019). *Agrobiodiversity Index Report 2019: Risk and Resilience*. Rome: Bioversity International

Cândido, G., Nóbrega, M., De Figueiredo, M., and Maior, M. (2015). Sustainability assessment of agroecological production units: a comparative study of IDEA and MESMIS methods. *Ambiente Sociedade*, 18, 99–118. doi: 10.1590/1809-4422ASOC756V1832015

Christiaensen, L. (2020). *Agriculture, Jobs, and Value Chains in Africa*. Jobs Notes, No. 9. Washington: World Bank.

COAG. (2018). *Agroecology: From Advocacy to Action*. Rome: Committee on Agriculture, Twenty-sixth Session, 1-5 October 2018.

Cochet, H. (2012). *Productivité, Les mots de l'agronomie, Histoire et Critique, INRA-SAD (dictionnaire en ligne)*. Available online at : https://mots-agronomie.inra.fr/index.php/Productivit%C3%A9

Cradock-Henry, N. A., Blackett, P., Hall, M., Johnstone, P., Teixeira, E., and Wreford, A. (2020). Climate adaptation pathways for agriculture: insights from a participatory process. *Environ. Sci. Policy* 107, 66–79. doi: 10.1016/j.envsci.2020.02.020

Damalas, C., and Koutroubas, S. (2016). Farmers' exposure to pesticides: toxicity types and ways of prevention. *Toxics*. 4:1. doi: 10.3390/toxics4010001

D'Annolfo, R., Gemmill-Herren, B., Gräub, B., and Garibaldi, L.A. (2017). A review of social and economic performance of agroecology. *Int. J. Agricult. Sustain*. 15, 632–644. doi: 10.1080/14735903.2017.1398123

De Olde, E., Oudshoorn, F., Sørensen, C., Bokkers, E. and De Boer, I. (2016). Assessing sustainability at farm-level: lessons learned from a comparison of tools in practice. *Ecol. Indicators* 66, 391–404. doi: 10.1016/j.ecolind.2016.01.047

De Pascuale Bovi, J., Álvarez, V. E., Hara, S. M., and Tittonell, P. (2019). *Testeo a campo de la herramienta de análisis de la transición a la agroecología TAPE en Patagonina*, Argentina. Bariloche: Giaasp, Instituto Nacional de Tecnología Agropecuaria (INTA)

Deaconu, A., Mercille, G. and Batal, M. (2019). The agroecological farmer's pathways from agriculture to nutrition: a practice-based case from ecuador's highlands. *Ecol. Food Nutr*. 58, 142–165. doi: 10.1080/03670244.2019.1570179

Deininger, K., Xia, F., and Holden, S. (2017). "ender-differentiated impacts of tenure insecurity on agricultural performance," in *Malawi's Customary Tenure Systems*. Washington: World Bank Policy Research Working Paper, 7943. doi: 10.1596/1813-9450-7943

Demeke, M., Meerman, J., Scognamillo, A., Romeo, A., and Asfaw, S. (2017). *Linking farm diversification to household diet diversification: Evidence from a sample of Kenyan ultra-poor farmers*. ESA Working Paper No. 17-01. Rome: FAO.

Dorin, B. (2017). India and Africa in the global agricultural system (1961-2050): towards a new sociotechnical regime. *Rev. Rural Affairs* 52, 5–13.

Ericksen, P.J. (2008). Conceptualizing food systems for global environmental change research. *Glob. Environ. Change* 18, 234–245. doi: 10.1016/j.gloenvcha.2007.09.002

Fanzo, J., Haddad, L., McLaren, R. Marshall, Q., Davis, C., Herforth A., et al. (2020). The food systems dashboard is a new tool to inform better food policy. *Nat. Food* 1, 243–246. doi: 10.1038/s43016-020-0077-y

FAO (2019d). *The State of the World's Biodiversity for Food and Agriculture*. Rome: Food and Agriculture Organization of the United Nations.

FAO and ADB. (2013). *Gender Equality and Food Security–Women's Empowerment as a Tool Against Hunger*. Rome: Food and Agriculture Organization of the United Nations.

FAO and FHI 360. (2016). *Minimum Dietary Diversity for Women: A Guide to Measurement*. Rome: Food and Agriculture Organization of the United Nations.

FAO, IFAD, UNICEF, WFP and WHO. (2020). *The State of Food Security and Nutrition in the World 2020. Transforming Food Systems for Affordable Healthy Diets*. Rome: FAO.

FAO and UNSD. (2012). *System of Environmental-Economic Accounting for Agriculture, Forestry and Fisheries: SEEA AFF (White Cover Version)*. Rome: Food and Agriculture Organization of the United Nations.

FAO. (2005). *The Importance of Soil Organic Matter: Key to Drought-Resistant Soil and Sustained Food and Production*. Rome: FAO Soils Bulletin 80.

FAO. (2011). *The State of Food and Agriculture 2010-11*. Rome: Food and Agriculture Organization of the United Nations.

FAO. (2014). *SAFA: Sustainability Assessment of Food and Agriculture Systems (Guidelines)*. Rome: Food and Agriculture Organization of the United Nations.

FAO. (2015a). *Decent Work Indicators for Agriculture and Rural Areas: Conceptual Issues, Data Collection Challenges and Possible Areas for Improvement*. Rome: FAO Statistics Division.

FAO. (2015b). *Self-Evaluation and Holistic Assessment of Climate Resilience of Farmers and Pastoralists*. Rome: Food and Agriculture Organization of the United Nations.

FAO. (2016a). *Greenhouse Gas Emissions and Fossil Energy use from Poultry Supply Chains: Guidelines for Assessment*. Rome: Livestock Environmental Assessment and Performance Partnership.

FAO. (2016b). *Greenhouse Gas Emissions and Fossil Energy use from Small Ruminant Supply chains: Guidelines for Assessment*. Rome: Livestock Environmental Assessment and Performance Partnership.

FAO. (2016c). *Migration, Agriculture and Rural Development: Addressing the Root Causes of Migration and Harnessing Its Potential for Development*. Rome: Food and Agriculture Organization of the United Nations.

FAO. (2017a). *The Future of Food and Agriculture: Trends and Challenges*. Rome: Food and Agriculture Organization of the United Nations.

FAO. (2017b). *Soil Organic Carbon: The Hidden Potential*. Rome: Food and Agriculture Organization of the United Nations.

FAO. (2018a). *The 10 Elements of Agroecology: Guiding the Transition to Sustainable Food and Agriculture Systems*. Rome: Food and Agriculture Organization of the United Nations.

FAO. (2018b). *SDG Indicator 2.4.1: Proportion of Agricultural Area Under Productive and Sustainable Agriculture (Methodological Note)*. Rome: Inter-Agency and Expert Group on SDG indicators, 6th November 2018.

FAO. (2018c). *Measuring SDG Indicator 5.a.1: Background Paper*. Rome: Food and Agriculture Organization of the United Nations.

FAO. (2019a). *TAPE: Tool for Agroecology Performance Evaluation. Process of Development and Guidelines for Application (test version)*. Rome: Food and Agriculture Organization of the United Nations.

FAO. (2019b). *Water Use in Livestock Production Systems and Supply Chains: Guidelines for Assessment*. Rome: Livestock Environmental Assessment and Performance Partnership.

FAO. (2019c). *Methodology for Computing and Monitoring the Sustainable Development Goal Indicators 2.3.1 and 2.3.2*. Rome: FAO Statistics Working Paper Series/18-14.

Farnworth, C.R., and Colverson, K.E. (2016). Building a gender-transformative extension and advisory facilitation system in sub-Saharan Africa. *J. Gender Agricult. Food Sec*. 1, 20–39. doi: 10.19268/JGAFS.112015.2

Francis, C., Lieblein, G., Gliessman, S., Breland, T.A., Creamer, N., Harwood, R., et al. (2003). Agroecology: the ecology of food systems. *J. Sustain. Agricult*. 22, 99–118. doi: 10.1300/J064v22n03_10

Gangemi, S., Miozzi, E., Teodoro, M., Briguglio, G., De Luca, A., Alibrando, C., et al. (2016). Occupational exposure to pesticides as a possible risk factor for the development of chronic diseases in humans (review). *Mol. Med. Rep*, 14, 4475–4488. doi: 10.3892/mmr.2016.5817

Gliessman, S. (2015). *Agroecology: the Ecology of Sustainable Food Systems. 3rd Edn.* Boca Raton, FL: CRC Press, Taylor & Francis Group. doi: 10.1201/b17881

Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M., Thornton, P., et al. (2013). Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proc. Natl. Acad. Sci.U.S.A.* 110, 20888–20893. doi: 10.1073/pnas.1308149110

Herrero, M., Thornton, P., Power, B., Bogard, J., Remans, R., Fritz, S., et al. (2017). Farming and the geography of nutrient production for human use: a transdisciplinary analysis. *Lancet Planet Health* 1, e33–42. doi: 10.1016/S2542-5196(17)30007-4

HLPE. (2017). *Nutrition and food systems. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security* (Rome).

HLPE. (2019). *Agroecological and Other Innovative Approaches for Sustainable Agriculture and Food Systems That Enhance Food Security And nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security* (Rome).

IFPRI. (2012). *Women's Empowerment in Agriculture Index*. Washington: International Food Policy Research Institute.

IFPRI. (2015). *Instructional Guide on the Abbreviated Women's Empowerment in Agriculture Index (A-WEAI).* Washington: International Food Policy Research Institute.

ILO. (2018). *Decent Work and the Sustainable Development Goals: A Guidebook on SDG Labour Market Indicators.* Geneva: International Labour Organization.

Jacobi, J., Mukhovi, S., Llanque, A., Augstburger, H., Käser, F., Pozo, C., et al. (2018). Operationalizing food system resilience: an indicator-based assessment in agroindustrial, smallholder farming, and agroecological contexts in Bolivia and Kenya. *Land Use Policy* 79, 433–446. doi: 10.1016/j.landusepol.2018.08.044

Jones, A., Shrinivas, A., and Bezner-Kerr, R. (2014). Farm production diversity is associated with greater household dietary diversity in Malawi: findings from nationally representative data. *Food Policy* 46, 1–12. doi: 10.1016/j.foodpol.2014.02.001

Kerr, R. B., Hickey, C., Lupafya, E., and Dakishoni, L. (2019b). Repairing rifts or reproducing inequalities? agroecology, food sovereignty, and gender justice in Malawi. *J. Peasant Stud.* 46, 1499–1518. doi: 10.1080/03066150.2018.1547897

Kerr, R. B., Kangmennaang, J., Dakishoni, L., Nyantakyi-Frimpong, H., Lupafya, E., Shumba, L., et al. (2019a). Participatory agroecological research on climate change adaptation improves smallholder farmer household food security and dietary diversity in Malawi. *Agric. Ecosyst. Environ.* 279, 109–121. doi: 10.1016/j.agee.2019.04.004

Kerr, R. B., Young, S., Young, C., Santoso, V, Magalasi, M, Entz, M, et al. (2019c). Farming for change: developing a participatory curriculum on agroecology, nutrition, climate change and social equity in Malawi and Tanzania. *Agricult. Hum. Values* 36, 549–566. doi: 10.1007/s10460-018-09906-x

Lachat, C., Raneri, J., Smith, K., Kolsteren, P., Van Damme, P., Verzelen, K., et al. (2018). Dietary species richness as a measure of food biodiversity and nutritional quality of diets. *Proc. Natl. Acad. Sci. U.S.A*. 115, 127–132. doi: 10.1073/pnas.1709194115

Lekei, E. E., Ngowi, A. V., and London, L. (2014). Farmers' knowledge, practices and injuries associated with pesticide exposure in rural farming villages in Tanzania. *BMC Public Health* 14:389. doi: 10.1186/1471-2458-14-389

Levard, L., Bertrand, M., and Masse, P. (2019). *Mémento pour l'évaluation de l'agroécologie: Méthodes pour évaluer ses effets et les Conditions De Son Développement*. Paris: GTAE-AgroParisTech-CIRAD-IRD

Leyva, A., and Lores, A. (2018). Assessing agroecosystem sustainability in Cuba: a new agrobiodiversity index. *Element. Sci. Anthr.* 6:80. doi: 10.1525/elementa.336

López-Ridaura, S., Masera, O., and Astier, M. (2002). Evaluating the sustainability of complex socio-environmental systems. The MESMIS framework. *Ecol. Indicators* 2, 135–148. doi: 10.1016/S1470-160X(02)00043-2

Losch, B. (2016). *Structural Transformation to Boost youth Labour Demand in sub-Saharan Africa: The Role of Agriculture, Rural Areas and Territorial Development.* Geneva: International Labour Office, Employment Policy Department, Employment and Labour Market Policies Branch

Lucantoni, D. (2020). Transition to agroecology for improved food security and better living conditions: case study from a family farm in Pinar del Río, Cuba. *Agroecol. Sustain. Food Syst*. 44, 1124–1161. doi: 10.1080/21683565.2020.1766635

Luna-González, D., and Sørensen, M. (2018). Higher agrobiodiversity is associated with improved dietary diversity, but not child anthropometric status, of Mayan Achí people of Guatemala. *Public Health Nutr.* 21, 2128–2141. doi: 10.1017/S1368980018000617

LVC. (2016). *Zero Budget Natural Farming in India*. Jakarta: La Vía Campesina

MAONIC. (2019). Manual Técnico Agroecológico. Managua: Movimiento de Productoras y Productores Agroecológicos y Orgánicos de Nciaragua.

Méndez, V.E., Bacon, C.M., and Cohen, R. (2013). Agroecology as a transdisciplinary, participatory, and action-oriented approach. *Agroecol. Sustain. Food Syst.* 37, 3–18. doi: 10.1201/b19500-2

Michalscheck, M., Groot, J., Fischer, G., and Tittonell, P. (2020). Land use decisions: by whom and to whose benefit? A serious game to uncover dynamics in farm land allocation at household level in Northern Ghana. *Land Use Policy* 91:104325. doi: 10.1016/j.landusepol.2019.104325

Michalscheck, M., Groot, J. C., Kotu, B., Hoeschle-Zeledon, I., Kuivanen, K., Descheemaeker, K., et al. (2018). Model results versus farmer realities. Operationalizing diversity within and among smallholder farm systems for a nuanced impact assessment of technology packages. *Agricult. Syst.* 162, 164–178. doi: 10.1016/j.agsy.2018.01.028

Migliorini, P., Galioto, F., Chiorri, M. and Vazzana, C. (2018). An integrated sustainability score based on agro-ecological and socioeconomic indicators. A case study of stockless organic farming in Italy. *Agroecol. Sustain. Food Syst.* 42, 859–884. doi: 10.1080/21683565.2018.1432516

Modernel, P., Dogliotti, S., Alvarez, S., Corbeels, M., Picasso, V., Tittonell, P., et al. (2018). Identification of beef production farms in the Pampas and Campos area that stand out in economic and environmental performance. *Ecol. Indicators* 89, 755–770. doi: 10.1016/j.ecolind.2018.01.038

Musumba, M., Grabowski, P., Palm, C., and Snapp, S.S. (2017). *Guide for the Sustainable Intensification Assessment Framework*. Washington: Feed the Future.

Nguyen, P.H., Avula, R., Ruel, M.T., Saha, K.K., Ali, D., Mai Tran, L., et al. (2013). Maternal and child dietary diversity are associated in Bangladesh, Vietnam, and Ethiopia. *J. Nutr.* 143, 1176–1183. doi: 10.3945/jn.112.172247

Nicholls, C., Altieri, M., Dezanet, A., Lana, M., Feistauer, D., and Ouriques, M. (2004). "A rapid, farmer-friendly agroecological method to estimate soil quality and crop health in vineyard systems". *Biodynamics*. 2004.

Novotny, I. P., Fuentes-Ponce, M. H., Tittonell, P., Lopez-Ridaura, S., Rossing, W. A. H. (2020). Back to the people: the role of community-based responses in shaping landscape trajectories in Oaxaca, Mexico. *Land Use Policy* 100:104912. doi: 10.1016/j.landusepol.2020.104912

OECD. (2019). *Purchasing Power Parities (PPP).* Available online at: http://data.oecd.org/conversion/purchasing-power-parities-ppp.htm (accessed June 24, 2020).

Oliver, B. (2016). "The earth gives us so much": agroecology and rural women's leadership in uruguay. *Cult. Agricult. Food Environ.* 38, 38–47. doi: 10.1111/cuag.12064

Ollivier, G., and Bellon, S. (2013). Dynamiques paradigmatiques des agricultures écologisées dans les communautés scientifiques internationales. *Nat. Sci. Soc.* 21, 166–181. doi: 10.1051/nss/2013093

PAN. (2015). *Replacing Chemicals With Biology: Phasing out hazardous pesticides with agroecology*. London: Pesticide Action Network.

PAR. (2018). *Assessing Agrobiodiversity: A Compendium of Methods.* Rome: Platform for Agrobiodiversity Research.

Peano, C., Migliorini, P., and Sottile, F. (2014). A methodology for the sustainability assessment of agri-food systems: an application to the Slow Food Presidia project. *Ecol. Soc.* 19:24. doi: 10.5751/ES-06972-190424

Pengue, W., and Gemmill-Herren, B. (2018). "*Eco-agrifood Systems': Today's Realities and Tomorrow's Challenges*," in *TEEB for Agriculture & Food: Scientific and Economic Foundations.* Geneva: UN Environment.

Petersen, P., Marçal da Silveira, L., Bianconi Fernandes, G, and Gomes de Almeida, S. (2020). *Lume: A Method for the Economicecological Analysis of Agroecosystems*. Centre for Agroecology, Water and Resilience (CAWR), Coventry University.

Pheap., S., Lefèvre, C., Thoumazeau, A., Leng, V., Boulakia, S., et al. (2019). Multi-functional assessment of soil health under conservation agriculture in Cambodia. *Soil Tillage Res.* 194:104349.

Pimbert, M.P. (2018). *Food Sovereignty, Agroecology and Biocultural Diversity. Constructing and Contesting Knowledge*. Abingdon; New York, NY: Routledge. doi: 10.1016/j.still.2019.104349

Place, F., and Otsuka, K. (2001). Tenure, agricultural investment, and productivity in the customary tenure sector of Malawi. *Econ. Dev. Cult. Change* 50, 77–99. doi: 10.1086/321918

Powell, B., Thilsted, S., Ickowitz, A., Termote, C., Sunderland, T., and Herforth A. (2015). Improving diets with wild and cultivated biodiversity from across the landscape. *Food Sec.* 7, 535–554. doi: 10.1007/s12571-015-0466-5

Praneetvatakul, S., Schreinemachers, P., Pananurak, P. and Tipraqsa, P. (2013). Pesticides, external costs and policy options for Thai agriculture. *Environ. Sci. Policy* 27,103–113. doi: 10.1016/j.envsci.2012.10.019

Ross, J., Driver, J., Lunchick, C., and O'Mahony, C. (2015). Models for estimating human exposure to pesticides. *Outlooks on Pest Management* 26, 33–37. doi: 10.1564/v26_feb_09

Sauermann, H., Katrin, V., Vyron, A., Bálint, B., Claudia, G., Kostas, K., et al. (2020). Citizen science and sustainability transitions. *Res. Policy* 49:103978. doi: 10.1016/j.respol.2020.103978

Schader, C., Grenz, J., Meier, M., and Stolze, M. (2014). Scope and precision of sustainability assessment approaches to food systems. *Ecol. Soc.* 19:42. doi: 10.5751/ES-06866-190342

Sickles, R., and Zelenyuk, V. (2019). *Measurement of Productivity and Efficiency: Theory and Practice*. Cambridge: Cambridge University Press. doi: 10.1017/9781139565981

Smith, L., and Haddad, L. (2015). Reducing child undernutrition: past drivers and priorities for the post- MDG Era. *World Dev. V* 68, 180–204. doi: 10.1016/j.worlddev.2014.11.014

Sourisseau, J.M. (2014). "Système d'activités et "sustainable rural livelihood" (SRL)," in *Élevages et territoires: Concepts, méthodes, outils*. ed Etienne Michel (Paris: INRA) 109–120

TEEB. (2018). *TEEB for Agriculture and Food: Scientific and Economic Foundations*. Geneva: UN Environment.

Teillard, F., Anton, A., Dumont, B., Finn, J.A., Henry, B., Souza, D.M., et al. (2016). *A Review of Indicators and Methods to Assess Biodiversity – Application to Livestock Production at Global Scale.* Rome: Livestock Environmental Assessment and Performance (LEAP) Partnership.

Teixeira, H. M., van den Berg, L., Cardoso, I. M., Vermue, A. J., Bianchi, F. J. J. A., Pena-Claros, M., et al. (2018). Understanding Farm Diversity to Promote Agroecological Transitions. *Sustainability* 10:4337. doi: 10.3390/su10124337

Thoumazeau, A., Bessou, C., Revenier, M.S., Panklang, P., Puttaso, P., Peerwat, M., et al. (2019). Biofunctool®: a new framework to assess the impact of land management on soil quality. Part B: investigating the impact of land management of rubber plantations on soil quality with the Biofunctool® index. *Ecol. Indicators* 97, 429–437. doi: 10.1016/j.ecolind.2018.10.028

Timler, C., Alvarez, S., DeClerck, F., Remans, R., Raneri, J., Estrada Carmona, N., et al. (2020). Exploring solution spaces for nutrition-sensitive agriculture in Kenya and Vietnam. *Agricult. Syst.* 180:102774. doi: 10.1016/j.agsy.2019.102774

Tittonell, P. (2020). Assessing resilience and adaptability in agroecological transitions. *Agric. Syst.* 184:102862. doi: 10.1016/j.agsy.2020.102862

Trabelsi, M., Mandart, E., Le Grusse, P., and Bord, J. P. (2016). How to measure the agroecological performance of farming in order to assist with the transition process. *Environ. Sci. Pollut. Res.* 23, 139–156. doi: 10.1007/s11356-015-5680-3

UNDESA (2019). *International Migrant Stock 2019. On-line database* Available online at: https://www.un.org/en/development/desa/population/migration/data/estimates2/estimates19.asp

UNEP. (2016). *Food Systems and Natural Resources. A Report of the Working Group on Food Systems of the International Resource Panel* (Nairobi).

UTT. (2014). *Manual "Conociendo al Suelo", Serie Agricultura Regenerativa*. Tula: Universidad Tecnológica de Tula-Tepeji.

Van der Ploeg, J.D., Barjolle, D., Bruil, J., Brunori, G., C. Madureira, L.M., Dossein, J., et al. (2019). The economic potential of agroecology: empirical evidence from Europe. *J. Rural Stud.* 71, 46–61. doi: 10.1016/j.jrurstud.2019.09.003

Vonthron S, Perrin C, and Soulard C-T (2020) Foodscape: a scoping review and a research agenda for food security-related studies. *PLoS ONE* 15:e0233218. doi: 10.1371/journal.pone.0233218

Waichman, A. V., Eve, E., and da Silva Nina, N. C. (2007). Do farmers understand the information displayed on pesticide product labels? A key question to reduce pesticides exposure and risk of poisoning in the Brazilian Amazon. *Crop Protect.* 26, 576–583. doi: 10.1016/j.cropro.2006.05.011

Wezel, A., Bellon, S., Doré, T., Francis, C., Vallod, D., and David, C. (2009). Agroecology as a science, a movement and a practice. A review. *Agron. Sust. Dev*. 29, 503–515. doi: 10.1051/agro/2009004

World Bank (2013). *World Development Report: Jobs*. Washington: World Bank Group.

World Health Organization (2010). *Exposure to Highly Hazardous Pesticides: A Major Public Health Concern.*

World Health Organization. (2020). *The WHO Recommended Classification of Pesticides by Hazard and Guidelines to Classification 2019*. Geneva: World Health Organization.

Zahm, F., Viaux, P., Vilain, L., Girardin, P., and Mouchet, C. (2008). Assessing farm sustainability with the IDEA method–from the concept of agriculture sustainability to case studies on farms. *Sustain. Dev.* 16, 271–281. doi: 10.1002/sd.380

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Agroecology in Large Scale Farming—A Research Agenda

Pablo Tittonell[1,2,3]*, Gervasio Piñeiro[4,5], Lucas A. Garibaldi[6,7], Santiago Dogliotti[8], Han Olff[2] and Esteban G. Jobbagy[9,10]

[1] Agroecology, Environment and Systems Group, Instituto de Investigaciones Forestales y Agropecuarias de Bariloche (IFAB), Instituto Nacional de Tecnología Agropecuaria – Consejo Nacional de Investigaciones Científicas y Técnicas, San Carlos de Bariloche, Argentina, [2] Conservation Ecology Group, Groningen Institute of Evolutionary Life Sciences, Groningen University, Groningen, Netherlands, [3] Agroécologie et Intensification Durable (AïDA), Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), Université de Montpellier, Montpellier, France, [4] Facultad de Agronomía, Instituto de Investigaciones Fisiológicas y Ecológicas Vinculadas a la Agricultura, Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Universidad de Buenos Aires, Buenos Aires, Argentina, [5] Departamento de Sistemas Ambientales, Facultad de Agronomía, Universidad de la República, Montevideo, Uruguay, [6] Universidad Nacional de Río Negro and Consejo Nacional de Investigaciones Científicas y Técnicas (UNRN-CONICET), Instituto de Investigaciones en Recursos Naturales, Agroecología y Desarrollo Rural, San Carlos de Bariloche, Argentina, [7] Instituto de Investigaciones en Recursos Naturales, Universidad Nacional de Río Negro, Agroecología y Desarrollo Rural, Río Negro, Argentina, [8] Departamento de Producción Vegetal, Facultad de Agronomía, Universidad de la República, Montevideo, Uruguay, [9] Grupo de Estudios Ambientales, Instituto de Matemática Aplicada San Luis, Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), San Luis, Argentina, [10] South American Institute for Resilience and Sustainability Studies, Maldonado, Uruguay

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Edited by:
Hans Rudolf Herren,
Independent Researcher, Washington, DC, United States

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Didier Bazile,
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Florian Wichern,
Rhine-Waal University of Applied Sciences, Germany

***Correspondence:**
Pablo Tittonell
tittonell.pablo@inta.gob.ar

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Agroecology promises a third way between common global agriculture tradeoffs such as food production and nature conservation, environmental sustainability and ecosystem services. However, most successful examples of mainstreaming agroecology come from smallholder, family agriculture, that represents only about 30% of the world agricultural area. Mainstreaming agroecology among large scale farmers is urgently needed, but it requires addressing specific questions in research, technology and policy development to support sustainable transitions. Here we take stock of the existing knowledge on some key aspects necessary to support agroecological transitions in large scale farming, considering two contrasting starting points: highly subsidized and heavily taxed agricultural contexts, represented here by the examples of Western Europe and temperate South America. We summarize existing knowledge and gaps around service crops, arthropod-mediated functions, landscape and watershed regulation, graze-based livestock, nature-inclusive landscapes, and policy mechanisms to support transitions. We propose a research agenda for agroecology in large scale farming organized in five domains: (i) Breeding for diversity, (ii) Scalable complexity, (iii) Managing cycles beyond fields and farms, (iv) Sharing the cultivated landscape, and (v) Co-innovation with farmers, value chains and policy makers. Agroecology may result in a renewed impetus in large scale farming, to attract the youth, foster clean technological innovation, and to promote a new generation of large-scale farmers that take pride in contributing to feeding the world while serving the planet and its people.

Keywords: sustainability, intensification, agriculture, landscape, ecosystem services, South America, Europe

INTRODUCTION

As the extent and output of agriculture still grows to new global records, so does the awareness of societies on the multiple contributions of land ecosystems to human well-being. Agroecology, or the application of social and ecological principles for the design and management of sustainable agroecosystems, sits at the core of this tension promising one of the very few ways out from the current trade-offs between food production and security and the broader well-being of humans and nature. Over the last decades large scale farming led to increasing production but also caused substantial environmental degradation, as such increases were mostly based on its expansion onto natural areas and greater use of external inputs and other forms of intensified use (IPBES, 2019). Meanwhile agroecology developed and became most successful in small scale family farming, which contributes roughly more than half of the food consumed by humans by one estimate, farming on <30% of the agricultural land (Graeub et al., 2016; Lowder et al., 2019). The potential of agroecology to become a "third way" model, able to address the tradeoffs between food security and other ecosystem services has raised interest among governments, development agencies, scientists and farmers (e.g., HLPE, 2019; WWF, 2020 etc.). Yet, the necessary step for the expansion and global scaling of agroecological approaches needs to consider their adaptation to large-scale commercial contexts. While several enlightening examples exist, we think that an open but assertive research agenda is still needed.

Large scale farming, which occupies the majority of the global agricultural area, is defined here as the highly mechanized, commercial cropping and livestock keeping activities that take place in privately owned or rented land by an individual farmer, company or family enterprise. This sector is responsible for 70% of current deforestation, the largest share of agriculture-related GHG emissions and agricultural water use, and habitat disruption resulting in biodiversity loss (IPBES, 2019).

Although examples do exist of large-scale commercial farming that follows the principles of agroecology, both in the Americas and in Europe (Kleijn et al., 2019), a full transition toward agroecology in large scale farming entails yet a number of challenges. Among them, the lack of appropriate knowledge, management practices and technologies adapted to large field sizes, mechanized farming, several commercial and value chain impediments, and high dependence on external input technologies (often recommended by agronomic "advisors" provided by the companies that produce or commercialize those inputs, or profit from high outputs). An additional factor deterring a wide scale transition to agroecology among large scale farmers is the distortion created by financial measures such as production subsidies, mostly in the North and heavy taxation, mostly in the South. Western Europe, and the temperate regions of South America are conspicuous examples of these two end points, from heavily subsidized to heavily taxed agricultural systems.

Beyond market incentives, high input agriculture models in western Europe evolve and are shaped as the result of simultaneous top-down incentives and disincentives in the form of governmental subsidies, private credit loans, EU agri-environmental measures, regulations such as on nitrogen emissions or the EU Natura-2000 directive, or incentives for the maintenance of cultural heritage landscapes. However, high productivity per unit land or per animal is also often seen as a mark of "efficiency" by EU farmers and related sectorial actors, which has also deep-rooted bonds with traditional cultures and rural styles of living (van der Ploeg, 2013). This high productivity per animal or unit land is even frequently presented as being environmentally friendly, based on "land sparing" arguments, despite its very high environmental impact per unit area of farmland (Loconto et al., 2020). The pursue of high productivity results in elevated use of external inputs and consequent high environmental impacts per unit area in the production region, in spite of several EU regulations designed to mitigate them. A growing number of farmers and their associations, governments, and environmental NGOs tend to see agroecology as an opportunity to reduce environmental impacts (e.g., nitrogen emissions, biodiversity loss) while continuing to maintain current productivity levels.

In the Pampas and Campos natural regions of Argentina, Brazil and Uruguay large scale, export-oriented agriculture and livestock systems contribute substantially to the national economies and represent an important source of livelihood and incomes. As these systems operate without any form of subsidy, economic efficiency is a central attribute to their functioning and long-term sustainability. In the case of Argentina, for example, tax policies impose a heavy burden on farmers, with export retentions of up to 30% for the dominant crops like soybean. While agroecology tends to draw the attention of large-scale South American farmers as a means to reduce production costs or risks of failure, possible yield penalties during the initial phases of the transition deters farmers from undertaking agroecology. In the absence of subsidies or other governmental incentives, any strategy oriented to support the transition to agroecology in large scale farming needs to secure incomes and profits from the very onset of the transition.

Our objective is to take stock of the knowledge available and identify key open research questions critical for the transition of large-scale farming systems to agroecology, from the realm of agronomy, ecology and social sciences. To do that, we will first describe the space of recommendation domains for large scale farming defined by the wide gradient from subsidized to taxed agricultural contexts, and their consequences for the resulting agricultural systems. We will briefly summarize the state of knowledge on six key areas of research that need to be addressed to inform the agroecological redesign of large-scale systems, namely:

(i) Multifunctional service crops;
(ii) Arthropod-mediated ecosystem services (from plot to landscape);
(iii) Watershed regulation and soil conservation (and restoration);
(iv) Regenerative grazed-based livestock systems;
(v) Nature inclusive agricultural landscapes;

(vi) Policy and finance to foster agroecological transitions.

We end by proposing an agenda and discussing the socio-technical and political implications that promoting such changes entail. We are aware that agroecological transitions and the necessary innovation systems are complex, adaptive, and entail multiple dimensions, actors and levels (cf. Tittonell, 2019, 2020). But instead of diving into socio-technical transitions, upscaling and their inherent complexity—which comprise a number of research questions in themselves—here we chose to focus on the more practical, end-user-oriented research questions that we receive in our daily practice from farmers, advisors, policy makers, and third sector organizations engaged in biodiversity and environmental sustainability.

INTENSIFICATION IN LARGE-SCALE AGRICULTURE

The design of agroecosystems based on the principles of the green revolution coined in the 60's focused almost exclusively on obtaining products that can be harvested, without a systemic look or evaluation of the social and environmental impacts of agriculture. Specialization resulted in a simplification of the agricultural landscape, with a consequent decline in its ability to deliver ecosystem services due to a gradual loss or degradation of the natural capital (e.g., Tsiafouli et al., 2015). Economic productivity measured as income and profit has been a major driver of agricultural intensification, especially but not exclusively in terms of input intensification. **Figure 1** presents a simplified model of the relationship between input intensification and (broad sense) economic productivity, measurable for example in terms of gross monetary income. The economically rational level of intensification would be, simplistically, that at which the maximum gross margin ($GM = income\ minus\ costs$) is attained. In many parts of the world, however, large scale intensive or industrial farming dominated by mono-cultures or intensive livestock husbandry has aimed at maximizing productivity (i_{max}; P_{max}), even at the expense of their gross margins, fueled by subsidies and other incentives, producing beyond the level of input intensification that an economic rationale would indicate (i_{opt}; P_{opt}—**Figure 1A**). High production costs and narrow margins lead to high risks of failure, which is normally absorbed by subsidies or other forms of economic compensation.

Following this simple, archetypal model, the effect of subsidies can be seen as a modification in the relationship between costs and productivity that creates the false impression that these systems are "efficient" because they are highly productive (**Figure 1B**); or worse, that the only way of achieving efficiency is through attaining the highest possible yields per unit land area or animal head. On the other hand, if the true costs of this form of agriculture were computed, that is, including their environmental and social externalities, then the responsible levels of optimum and maximum productivities and input intensification would be much lower than those of nowadays. At the other end of the gradient (**Figure 1C**), countries that tax agricultural exports render i_{max} intensification levels totally unprofitable, leading to the misinformed but common perception that government tax policies are the main reason for the economic failure of high input agriculture models. Under heavy taxation, however, the maximum GM would still be attainable at i_{opt} intensification levels according to this simplified production function.

Yet, maximum gross margins are not necessarily attained at environmentally or socially sustainable intensification levels. The model in **Figure 1** considers costs, income and margin but disregards the biophysical resource flows to and from the agricultural system, such as carbon, nutrients and water associated with the different levels of intensification. To do that, we added a new y-axis parallel to productivity that indicates increasing flows of these biophysical factors, necessary to maintain a balanced, sustainable use and long-term conservation of natural resources (**Figure 2A**). The ideal level of input intensification in this new model is indicated as i_{sust}, corresponding to a higher productivity (P_{sust}). This point, arbitrarily depicted as a half-way productivity between P_{opt} and P_{max} in **Figure 2A**, represents a level of input intensification that ensures for example soil nutrient replenishment through fertilization, greater flows of carbon from plant litter to soil, more efficient use of rainfall water, or more diversified feeds and/or direct foraging resulting in greater animal welfare in livestock systems. Such a higher level of intensification may not necessarily result in the widest margins nor in the highest productivity, but can be seen as an investment in maintaining the natural capital. Subsidies or tax policies could be in some cases an instrument to regulate intensification levels following this logic (**Figure 2A**). However, there is a limit to the ability of these instruments to shape sustainable forms of agriculture, and virtually none to promote by themselves a transition to agroecological farming.

Figure 2B illustrates a theoretical, full transition to agroecology of large-scale farms, in which the productivity increases as a result of "process" intensification (i_p), extending the notion of intensification to include the "intellectual" inputs that characterize agroecology, such as managing landscape complexity, diversity, synergies, natural regulation, and ecosystem services. Under process intensification, it is assumed that production costs do not grow linearly, as in the case of input-intensification, but they reach a plateau as the relative importance of processes in the system outgrows that of the minimum inputs. Optimal productivity would be closer to maximum productivity (*NB*: in a real agroecological system, productivity is measured for all different activities on the farm simultaneously, not just a single crop species, or a single activity such as annual cropping), providing a reasonable economic margin (GM) with low risk, and ideally with no financial debts. Intensifying beyond this point may not result in much higher overall productivity but in the long-term building of the natural capital of the system, in the form of fertile (often regenerated) soils, balanced water flows, greater biodiversity and positive biological interactions, quality habitats for wildlife species, carbon sequestration, etc. In other words, in a more efficient provision of ecosystem services of local and global importance, that may even result in lower production costs for farmers and/or in alternative sources of income in some cases, through

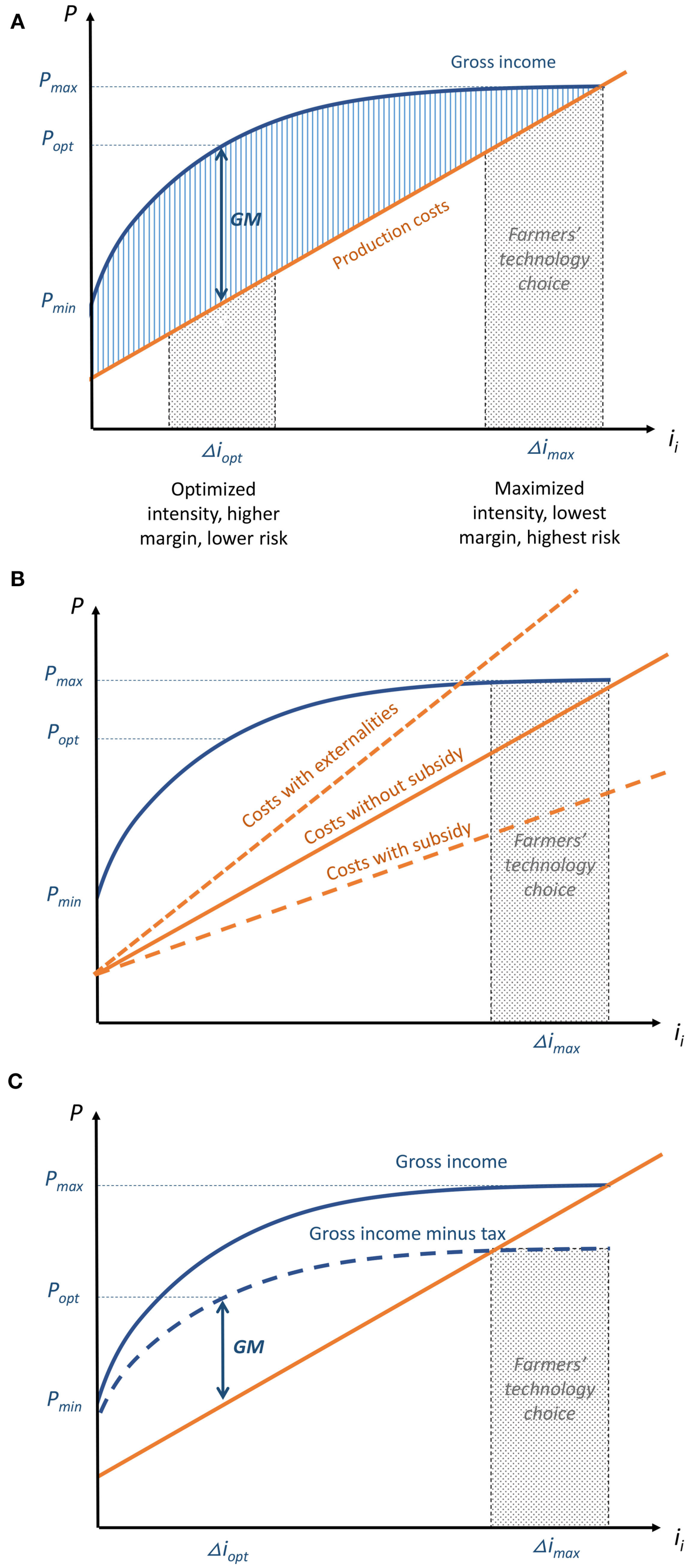

FIGURE 1 | Schematic representation of the relationship between level of input intensification (*i*) and productivity (*P*), for example in terms of gross monetary income. **(A)** The widest gross margins (*GM*) can be attained at lower than maximum productivity levels (P_{opt}), at a context-specific optimum level of intensification (i_{opt}); current

(Continued)

FIGURE 1 | farmers' preferred intensification level (i_{max}) however leads to high investment risks and narrower attainable margins, and increased intensification generally reduces ecosystem services and natural capital. **(B)** Countries or regions that subsidize their agriculture render i_{max} intensification levels apparently profitable, but if subsidies were removed or externality costs (social, environmental) internalized current technological choices would render the system unprofitable. **(C)** Countries that tax agricultural exports render i_{max} intensification levels totally unprofitable, leading to the misinformed perception that government tax policies are the main reason for the economic failure of such high input agriculture models (while maximum GM would still be attainable at i_{opt} intensification levels).

e.g., financial incentives for nature conservation, agro-tourism, etc.

In reality, however, a limited number of large-scale farmers are or would eventually be able to fully transition to agroecology relying exclusively on process technologies. A most plausible scenario, represented in **Figure 2C**, is one in which large scale farmers would use agroecological principles for a combined input and process intensification (i_{i+p}) of their system, making efficient use of ecosystem services to increase incomes and reduce costs. Under this model, there is a limit to intensification (i_{max}) beyond which economic productivity, measured as gross income, starts decreasing due to resource degradation, excessive pesticide inputs, loss of natural enemies and pollinators, resistance to pesticides or antibiotics, or other pollutants.

We hypothesize that agroecology can provide the tools and knowledge to make efficient use of the natural functionalities that ecosystems offer, so that the reliance on external inputs of non-renewable resources or toxic molecules can gradually decrease along a so-called ecological intensification trajectory (cf. Tittonell, 2014). Although several factors preventing the transition to agroecology among large scale farmers are political, commercial or even cultural, we still consider that current agricultural research, from breeding to agronomy, ecology or social sciences, has a number of urgent calls in order to inform, sustain, and promote transitions. In the following section, we highlight selected areas of knowledge that are currently providing, but also require more, innovation to inform such transitions. They form the basis of the research agenda for agroecology in large scale farming that we propose toward the end of this manuscript.

PROMISING AVENUES TO ENHANCE AGROECOLOGICAL TRANSITIONS

Multifunctional Service Crops

Traditional, pre-twentieth century agricultural practices were largely based on growing multiple plant species, several of them not to be harvested. Cover crops, green manures, trap crops, green bridges, and a variety of other multipurpose species are able to provide regulation and support ecosystem services, which are important locally (ecosystem services that affect agricultural production), regionally (ecosystem services that are provided by rural landscapes), or globally (ecosystem services that benefit humanity). These associated, non-harvested species or service crops represent a valuable—necessary but not sufficient—tool within agro-ecologically managed systems.

The benefits of service crops in terms of the provision of ecosystem services is well-known and recognized nowadays in the agricultural research community (Schipanski et al., 2014; Pinto et al., 2017; Garcia et al., 2018), but less so among large scale farmers. Agricultural census data in the Americas show that service crops were adopted in <5% of the total agricultural land (e.g., 3.9% in the US in 2017: Zulauf and Brown, 2019). Data from Europe indicate that cover crops, plant residues and multi-annual plants occupy shares of 8, 7, and 8% respectively in arable land during winter (EUROSTAT: online data code: EF_MP_SOIL, updated 03/08/2020). In Argentina, the area of cover crops is increasing rapidly from 4 to 5% until 2015 to 13% in the 2019/2020 season (Bolsa de Cereales, 2020), largely associated with conservation tillage practices. Among the reasons that farmers put forward for the limited adoption of service crops are the perceived extra costs associated with the practice, and the limited availability (and high price) of seeds of several species used as service crops in local markets. Yet there are also farmers that consider service crops as an investment, since they help to regenerate the structure and functioning of degraded agroecosystems, reduce external inputs costs, contribute to increasing agricultural productivity and long-term sustainability (Schipanski et al., 2014).

Most species and their cultivars used nowadays as service crops have been bred or improved usually for fodder production (Scholberg et al., 2010), and hence their plant architecture, growth habit, phenology or functional traits do not always respond to the objectives for which they are grown in agroecological schemes. To integrate service crops in agroecological design and management, breeding programs for multipurpose traits are urgently needed, taking into account desirable morphological attributes that can contribute to multiple objectives, such as deep rooting, high leaf to stem ratios (or the opposite according to needs), promiscuity in terms of symbiotic N fixation, drought resistance or high water use efficiency, short or long cycles, propensity for mycorrhizal infestations, attractiveness to pests and/or to natural enemies, competitive ability against weeds, allelopathy, etc. (Kell, 2011; Wayman et al., 2017). A major challenge in this regard is the potential tension between private and public, non-profit plant breeding programs, that shape interests and determine asymmetrical investments in breeding programs (Brummer et al., 2011). Programs should include breeding for in-field diversity, and participatory breeding programs where farmers take action in the selection of plans leading to rapid local developments and adoption (Weltzien and Christinck, 2017). In addition, there is need for further collaboration between plant breeders and ecologists to develop future cultivars that fulfill both food production and ecosystem services restoration and maintenance, which will require stable and long-term funding sources (Brummer et al., 2011).

Research is needed to functionally link plant traits with ecosystem service provision in the specific context of agroecological design and management, which implies that

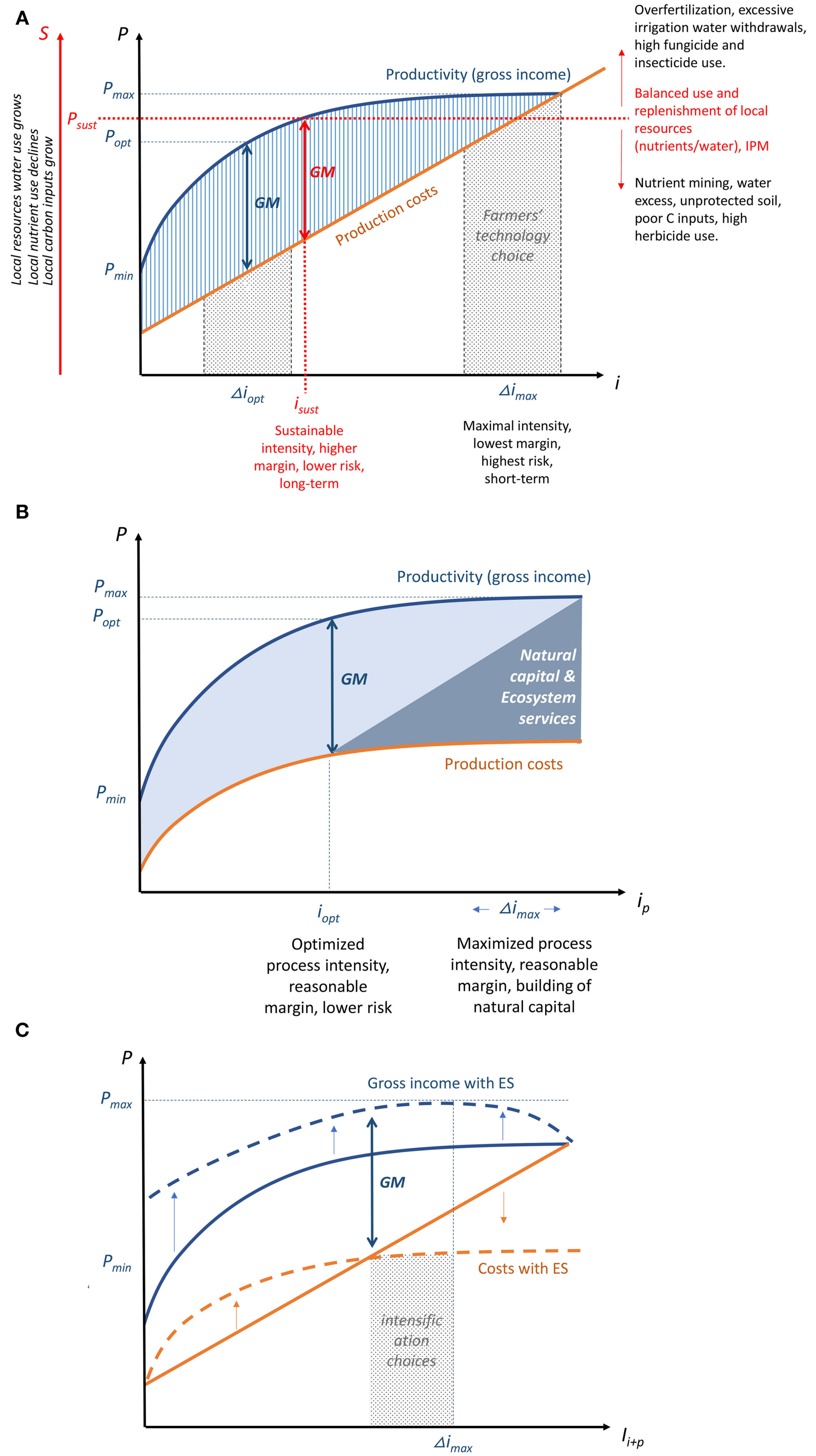

FIGURE 2 | Steps in the agroecological transition of large-scale farming systems. **(A)** First step consists of regulating productivity to address short- and long-term goals. A new y-axis (S) is added to the model of **Figure 1** that represents desirable shifts in terms of local resource use (water, nutrients, carbon) and a proposed

(Continued)

FIGURE 2 | 'sustainable' productivity level (P_{sust}) compatible with balanced, efficient water use while ensuring soil fertility maintenance (i_{sust}); costs are higher than economically optimal, but can be seen as investments in long term productivity. **(B)** Second step consists of a thorough agroecological redesign of the farming system to favor process- in detriment of input-intensification. A new model is proposed replacing input intensity (i_i) by process intensity (i_p) in the x-axis; optimal productivity is closer to maximum productivity, which allows a reasonably gross margin (*GM*); and further intensification beyond i_{opt} does not necessarily result in greater margins but in building of natural capital (i.e., long-term productivity) and greater provision of ecosystem services. **(C)** Combining input and process intensification using principles of agroecology to foster ecosystem services. Continuous lines indicate income and costs under current baseline (cf. **Figure 1A**) whereas dotted lines include the addition of ecosystem services to incomes and costs.

service crop and their mixtures should provide multiple functions simultaneously according to variable designs of the mixtures. In agroecological systems, service crops will be incorporated in heterogeneous space-time combinations that will affect the expression of different traits in the service plants, hence plasticity is important. Several research questions arise also from practice, for example:

- How to regulate cover/companion crops vigor in order to avoid competition with the main cash crops for space, water and nutrients, reduce air moisture to avoid plant diseases, especially in wetter climates;
- How to reduce soil water depletion by cover crops during winter in drier climates;
- How to improve cover crop establishment in the dry conditions of late summer;
- How to terminate (vigorous) cover crops, maintaining soil cover, while ensuring viable seeding and germination conditions for the main cash crop:
- Under which conditions are perennial service crops (e.g., grass-legume mixtures) and biomass transfers for mulching a viable alternative in ecological and economic terms;
- How can service crops periods be used to replenish soil nutrients, control weed seed banks, and/or regulate pest populations so as to benefit the main cash crops in the rotation;
- What extra specific traits are needed when service crops are incorporated in crop-livestock, agroforestry, or agro-silvo-pastoral systems?

These are just a few examples of questions that arise from practice. Next to them, there is also the major challenge of mechanizing these activities, several of which cannot be efficiently accomplished with the machinery currently available on the market.

Arthropod-Mediated Ecosystem Services

In large scale agriculture, larger field sizes are usually associated with landscape simplification, a main driver of the loss of arthropod species providing biological pest control or pollination services (Dainese et al., 2019; Martin et al., 2019). Garibaldi et al. (2016) presented consistent evidence that larger fields reduce arthropod-mediated ecosystem services. This global study quantified to what degree enhancing pollinator density and richness improved yields on 344 fields from 33 pollinator-dependent crop systems in small and large farms from Africa, Asia, and Latin America. Worldwide, the benefits of flower-visitor density to crop yield were greater for smaller than larger holdings, and when flower-visitor richness was higher. For fields of <2 hectares, it was found that yield gaps could be closed by a median of 24% through higher flower-visitor density. For larger fields, such benefits only occurred at high flower-visitor richness. Improving flower-visitor richness in large fields is a challenge that will require a combination of practices, the effectiveness of which is context dependent, including sowing flower strips and planting hedgerows, providing nesting resources, more targeted use of pesticides, and/or restoration of semi-natural and natural areas adjacent to crops (Garibaldi et al., 2014). A recent synthesis of 89 studies with 1,475 locations showed that pollinator and enemy richness directly supported ecosystem services in complementary ways to abundance and dominance (Dainese et al., 2019). This review shows that negative effects of landscape simplification on ecosystem services were importantly mediated by richness losses of service-providing organisms, with negative consequences for crop yields. Given the positive influence of edge density on arthropod communities providing biological pest control or pollination services (Martin et al., 2019). A possible way to counteract the negative effects of large fields is to design them in strips to increase edge density without compromising the amount of area effectively cropped. Promising experiences in this direction are increasingly being documented (e.g., Ditzler et al., 2020). When agroecological designs imply using field hedges as uncultivated habitat/feeding environments for beneficial organisms, the tradeoffs with potential agricultural productivity losses need to be weighed also against overall costs and risks at farm scale, in the short and the long terms.

Watershed Regulation and Soil Conservation

Agriculture and its multiple management practices influences the way in which water and its load of sediments, nutrients, salts and pollutants are routed through the landscape and the hydrological system. As a result, it affects the long-term performance of production (e.g., modulating soil erosion rates and rainfall infiltration—Basche and DeLonge, 2017) as well as critical ecosystem services such as water provision (e.g., amount, timing, quality) or the regulation of downstream aquatic systems (e.g., their hydrological regime or pollution levels). Some of the most promising interventions in large-scale agricultural systems regarding these impacts involve landscape designs in which croplands coexist with other fixed or rotating vegetation types including cultivated pastures, tree plantations, and natural vegetation. Key decisions in this regard include the fraction, grain, and landscape position in which these non-agricultural patches are located, in order to mitigate the most concerning degradation processes.

In small watersheds of the North American corn-belt, 10% area of prairie filter strips either at foot slopes or contour strips were sufficient to cut run-off and sediment transport by 30 and 95%, respectively, in the dominant simplified farming systems, improving water availability for crops, protecting soils and water quality, and providing many additional services (Helmers et al., 2012; Schulte et al., 2017). In the drier part of the flat plains of Argentina, relatively low intensity farming systems with long fallows and extremely simplified landscapes, experience gradual water table level raises that end in massive waterlogging and salinization (Jobbágy et al., 2008; Nosetto et al., 2012; Kuppel et al., 2015). Sustaining evapotranspiration from waterlogged areas in wet years with dedicated natural wetland areas, or through the inclusion of flood-tolerant service crops, and "rescuing" deeply recharged water in dry years with native forest patches or rotating deep rooted grasslands are viable options to regulate a deleterious hydrological shift that damages farmland, infrastructure, and settlements (Mercau et al., 2013; Nosetto et al., 2015; Giménez et al., 2016). In more intensified settings in Europe and North America, ditch networks can be designed (e.g., density, topology) and managed (e.g., dredging, weeding/mowing regime) in a way that simultaneously regulates waterlogging and provides water cleaning, hydrological regulation, and habitat protection services (Dollinger et al., 2015). Plot to whole farm level designs that include patches of non-agricultural vegetation should be accompanied by whole watershed initiatives that include an explicit design (width/length/vegetation type) of riparian corridors (Cole et al., 2020).

As explicit landscape design becomes embraced by farmers and land and water policy makers, many questions will emerge. From a biophysical standpoint, developing reliable functions that depict how ecosystem services (e.g., water flow magnitude and timing; or sediment, nutrient, and pollutant loads) respond to the fraction of different types of non-agricultural land covers that are included in the landscape, is an ambitious but critical target, that can be approached gradually through adaptive management strategies in which interventions are used as experiments and modeling frameworks are used to integrate knowledge (e.g., Groot et al., 2016). For this reason, explicit monitoring and comparison plans are crucial in large-scale farming systems shifting toward agroecological management. These strategies need to consider the episodic nature of many disservices such as massive erosion and sediment transport, which can be assessed sporadically.

Landscape level non-linearities are among the most difficult but also promising aspects of watershed management. For example, pure forests and pure cropland may display a hydrological balance that is not maintained when they coexist as a patchwork in the landscape. Understanding aerial, surface and subsurface lateral transport of energy, water, and nutrients in increasingly complex farming landscapes is still an open challenge. From a human standpoint, knowledge on the perception and values of farmers and settlers regarding different land covers and landscape arrangements is also critical to achieve sound agreements or at least steer negotiations. Where watersheds are larger than individual farms, understanding how neighbors distribute the costs and benefits of agroecological landscape designs is a necessary step to develop sustainable incentives and agreements. Finally, a "fractal" approach to landscape diversification, in which tools from the realms of precision agriculture (within plot), landscape design (across plots), and watershed management (whole landscape) are integrated, is a promising avenue for further research to support agroecological transitions in large scale farming.

Regenerative Graze-Based Livestock Systems

Transition to agroecology in graze-based livestock systems may provide a way to increase productivity and income without increasing the use of external inputs and risks, to restore the productivity of degraded or overgrazed grasslands, and at the same time enhancing the provision of ecosystem services. For example, simply organizing the herd and the grazing regime to increase forage allowance, forage height, and plant biomass leads to enhanced energy consumption per animal and forage production by native grassland species (Carvalho et al., 2011; Carriquiry et al., 2012; Do Carmo et al., 2016). Other agroecological strategies include matching grassland growth rates during the year with forage demands by different animal categories, multi-species grazing designs to stimulate complementarity, matching spatial heterogeneity to different quantity and quality of forage requirements, respecting reseeding, and maintaining a permanent soil cover, all of which have proven successful at both experimental and real farm conditions, doubling current productivity levels (e.g., Albicette et al., 2017; Do Carmo et al., 2018). These transitions require also animal breeding support, an agenda that has been highlighted for ruminants, pigs and poultry (Phocas et al., 2016). Yet, as in the case of cropping systems, two broadly distinct approaches are needed for the agroecological transition of livestock systems in currently extensive vs. intensive production systems and contexts.

Livestock production based on native grasslands as the main source of animal nutrition is an example of large-scale farming producing meat, wool, and leather with low inputs of chemical fertilizers, fossil energy, and pesticides (Picasso et al., 2014). This form of privately-owned livestock operation is often referred to as ranching, and it is more common in the Americas than in Europe. Large areas of tropical forest are being cleared for the establishment of pasture lands, particularly in Brazil's Amazon and Mato Grosso regions (Pinillos et al., 2020). Here, however, we refer to native grasslands, areas that have not been forests since the last glacial period. Such is the case of the Rio de la Plata grasslands, i.e., the grassland biome that covers south Brazil, North East Argentina and the whole of Uruguay are a hotspot for biodiversity (Bilenca and Miñarro, 2004; Overbeck et al., 2007), and provide ecosystems services such as carbon sequestration, moderating regional climate, preserving the soil from erosion and maintaining water quality. However, the degree of ecosystem service provision across space and time and the tradeoffs between these and animal or economic productivity need to be more rigorously quantified (Tittonell et al., 2016). The sustainability of these grazing systems is threatened by overgrazing, which results in poor economic results, deterioration of the natural grassland, increased erosion rates, reduction of the carbon stock and increase in greenhouse gas emissions per unit area and product (Altesor et al., 2005; Overbeck et al., 2007; Modernel et al., 2018). This process has also increased the vulnerability of these systems to drought events (Modernel et al., 2019). While measures for their ecological intensification do exist and prove technically viable, their wide adoption by farmers is still challenging, no less due to the aging of this farming population and the gradual disappearance of this traditional lifestyle. When ranching farmers retire, the land is often leased out to agricultural enterprises that grow export crops (Albicette et al., 2017).

In intensive livestock systems and environments, where animal stocking rates are higher as sustained by external inputs such as in Europe, animal health and welfare considerations are central, as these affect production and product quality. Dumont et al. (2013) summarized key principles for the transition to agroecology in such animal production systems:

(i) Management practices that improve animal health;
(ii) Decrease the amount of inputs needed for production;
(iii) Optimize the metabolic functioning of farming systems;
(iv) Enhancing diversity to strengthen resilience;
(v) Preserving biological diversity in agroecosystems.

Even in intensively managed sown pastures, that are normally simple grass-clover mixtures, plant species diversification (forbs) can greatly improve efficiency of nutrient use by plants and grazing animals, soil quality and biological activity (de Haas et al., 2019; Hoogsteen et al., 2020). Yet many of the benefits of plant diversity are only evident in the long term (e.g., Cardinale et al., 2007), which is not always compatible with the current management of short-lived (3 years) pastures within intensive rotations. As in the case of extensive livestock on native grasslands, regenerative management of intensive grasslands includes their species diversification, water table/runoff management, balanced combination of direct grazing and mechanical mowing during the year, sometimes mechanical interventions to loosen compacted soil and/or inter-sow desired grassland species, inclusion of trees and fodder shrubs (also relevant to improve animal health), nutrient restitution (preferably together with organic matter through solid manure), watershed protection, increased permanent soil cover, natural re-seeding enclosures, multi-species grazing, selection of animal breeds adapted to agroecological management, etc. Yet, an agroecological transition cannot be described as a blueprint recipe or a set of predefined steps to be followed. Farmers are diverse not only in their resource endowment, socio-economic and bio-physical environments but also in their ability to experiment, modify, and adapt technologies to their conditions.

Nature Inclusive Agricultural Landscapes

The trade-off between increased productivity through increased inputs vs. declining ecosystem services and natural capital summarizes a complex underlying process of changing species-environment relations. Different species groups are differentially sensitive to agricultural intensification; some plants, invertebrates, and bird species can still find a (temporal) habitat in large-scale agriculture, while others cannot. These differences reflect underlying niche differences between species in their relations with environmental factors modified by agriculture, such as nutrient availability, soil pH, hydrology, and disturbance regimes. For example, plants or insects that have natural habitats with stable, low nutrient inputs as temperate peat bogs, and tropical upland forests, will be much more sensitive to agricultural intensification than species that evolved under more nutrient rich and dynamic conditions, such as riverine floodplains and shores. In such habitats, large-scale agricultural intensification can lead to complete species replacement of the local species pool, in many cases by invasive species from other continents (Mack et al., 2000).

Higher nutrient inputs generally lead to less coexistence opportunities for different plant species, as competition shifts from several belowground resources to mostly for light, often with a single-best competitor (Tilman, 1988). Reductions of inputs will therefore not only add species to the local species pool, but also cause turnover of species that are better adapted to the new conditions. Less diversity of plants is generally associated with less diversity of invertebrates due to less resource diversity for specialized species, and can lead to a decline of soil biodiversity and associated ecosystem services as soil fertility. Various recent studies show a strong decline of both insect biomass and insect diversity with a potential cause in agricultural intensification (Hallmann et al., 2017), as in increased inputs of nutrients and pesticides.

For birds that are mobile, large-scale agriculture can serve a key role during parts of their life cycle, such as a foraging ground during migration or as a breeding ground. But also for birds, agricultural intensification generally leads to a decrease in bird diversity, and their associated benefits as seed dispersal and pest control (Hendershot et al., 2020). Including agroecological principles in large-scale agriculture can potentially retain such benefits (Holland et al., 2016). In Northwestern Europe, meadow birds—associated with mostly dairy farming grasslands—have strongly declined, likely due to declining food availability for their mostly precocious young (independently foraging directly after hatching). While low-input flower-rich grasslands in spring provided a diversity of food for such species, high-input grasslands dominated by only a few productive grasses do not offer these opportunities anymore, where the combination of reduced food, increased disturbance frequency and enhanced predation due to changing food web structure are likely fatal (Kleijn et al., 2004; Kentie et al., 2016). Additionally, frequent mowing and often early in spring destroys the bird nesting habitats and offspring, resulting in severe population declines (Gill et al., 2007).

But too strong declines in nutrient availability is also not beneficial for such species as this leads to decreasing soil fauna as earthworms, an important food source; these species typically profit from low-input agricultural practices that may not be economically feasible anymore by generating too little net revenue. Efforts to generate new revenue models for combining payments for meadow bird protection with dairy farming (so payment for ecosystem services, see below) have until now show little success, as this species group is still in very strong decline (Howison et al., 2018).

Even large scale, high input agriculture can form a breeding habitat for some species of birds, even for highly endangered species such as Montagu's harrier or the short-eared owl (Koks et al., 2007). Such species can profit from the relative safety from predators of very large, uniform agricultural fields, given that suitable foraging habitat to feed the young is nearby. Especially when combined with active nest protection by volunteer groups, this can lead to the surprising return of nearly-extinct endangered raptors (Schlaich et al., 2015).

In summary, different species groups respond differently to the primary axis of intensification depicted in **Figure 1**, with generally a loss of diversity but also opportunities for particular endangered groups at different levels of agricultural inputs that still can be economically feasible. Protecting such species requires good knowledge of the life history and niche dimensions of these different species, and specific interventions aimed at protection of nests (delayed mowing, nest caging) have been deployed. However, this has not stabilized populations of these species until now, calling for alternative strategies for agroecological farming that is still compatible with preservation of some components of the biodiversity characteristics of historic agricultural landscapes. Examples do exist of nature-inclusive, yet high output farming in western Europe, such as in the intensive Dutch dairy sector on the Flevopolder (cf. **Figure 3**), combining diverse grasslands and vegetated waterways, solid manure applications, self-production of fodder and grain crops and adapted local breeds (Blaarkop × Holstein) of animals that live up to 15 years on the farm, with milk productivity levels in the order or 8 t animal^{-1} year^{-1}. Such examples are common in practice but unfortunately still seldomly documented in the scientific literature, and hence the actual tradeoffs between their economic viability and the other ecosystem services they provide remains an important research question to explore further.

Policies and Financial Mechanism to Foster Agroecological Transitions

Several policies have been developed and implemented in the contexts of both heavily taxed to highly subsidized agricultural systems. The effect of such policies in terms of promoting a transition to agroecological farming has been variable, but generally weak (**Figure 4**). In heavily taxed contexts, such as in the flatland regions of South America, tax reduction *per se* will not result in a transition to agroecology but probably the opposite (e.g., tax reduction on fertilizers), unless tax cuts are tied to the provision of specific ecosystem services or to agroecological transitions. Incentives for good agricultural practices may result in less and more efficient use of external inputs, but is not enough to promote a thorough transition to agroecology. Access to soft credits to finance agroecological transitions may have positive impacts, although their effectiveness will also depend on farmer accountability (i.e., to what extent are credit beneficiaries using the credit to finance agroecological transitions), which is more easily ensured in situations with strong institutions and where farmers are used to reporting their activities to the government every year. Government financed advice and support on agroecology, on the other hand, may have a greater effect in heavily taxed contexts, where agroecology is seen also as an opportunity to reduce production costs.

In the context of highly subsidized agriculture, subsidies for set aside or rewilding programs (which are, in a way, also a form of payment for ecosystem services) have had a timid effect on promoting more sustainable agricultural practices (Batáry et al., 2015). Government financed support and advice on agroecological transitions are likely to have a limited effect as well (**Figure 4**), since there is no real incentive for the transition under the current policy, regulatory and market environments (e.g., Stassart et al., 2018). Fines and other forms of disincentives for ecosystem dis-services, such as water or air pollution, may be a mechanism to promote more agroecological practices, provided that they are applied in combination with the development of alternative practices and technologies available to farmers (e.g., Deverre and de Sainte-Marie, 2008; Elzen et al., 2017; Ministére de l'Agriculture and de l'Agroalimentaire et de la Forét, 2017). Perhaps the most daring hypothesis proposed in **Figure 4** is that, in a context of heavily subsidized agriculture, an overall reduction of subsidies and the selective subsidy of agroecological practices and redesigns will have the greatest effect at fostering agroecological transitions.

DISCUSSION

A research agenda to support the transition to agroecology among large scale farmers should contemplate societal goals beyond economic productivity. There is an increasing awareness that agricultural land benefits to society are not just about food production (IPBES, 2019). However, given the pressing financial situation in which most large-scale farmers operate, and the fact that economic considerations often come up as a top priority in discussions with farmers, policy makers, and other sectoral actors, we took economic productivity as the entry point for our reflection on intensification pathways (cf. **Figures 1**, **2**). Also due to the increasing awareness among these actors that agroecology is able to reduce production costs and risks, while generating additional benefits to society as a whole (Wezel et al., 2018; WWF, 2018; Anderson et al., 2019). Our agenda goes however beyond simplified production functions as those used in **Figures 1**, **2**, and considers five domains in which research is most urgently needed (**Figure 5**). Specific innovation pathways can be then identified within these major domains, which correspond to different levels of integration and spatio-temporal scales.

From an agronomic perspective (domains I and II in **Figure 5**), research to support agroecological transitions should focus on increasing the diversity of available—and economically viable—production crops or animal breeds, leading to more options to farmers for diversification. This has been indicated as breeding for diversity in **Figure 5** but it entails also the smart use of existing genetic resources, such as native grass species as forage, natural fallows, locally adapted ancient cultivars as service plants, creole breeds of domestic animals and their backcrossings in marginal or low input environments, etc. Over the last decades, however, a large divergence of yield gains is

FIGURE 3 | Images of a nature-inclusive farm in the intensive polder farming area of Flevoland, in The Netherlands. **(A)** Highly diversified grasslands, combining grasses, legumes and forbs and grazed directly; **(B)** Monitoring and intensive management of water table levels throughout the year to create spatial heterogeneity; **(C)** Storing and composting of solid manure; **(D)** small water bodies necessary for insect and bird diversity, creating better conditions also for animals; **(E)** Stable with deep bedding system (straw), free gates in and out and free access to a milking robot (in red, at the back); **(F)** Adapted, on farm bred herd combining Blaarkop (local breed) and Holstein lines, merging productivity, longevity and rusticity; **(G)** Interconnected biodiversity corridors throughout the farm. Pictures taken in September 2020 by P. Tittonell.

seen in mainstream crops like dented maize vs. flint maize or sorghum that are left behind (Parra et al., 2020), not to mention non-soy legumes (Shunmugam et al., 2018). Breeding for diversity implies then including more crop species in the portfolio of the strongest breeding institutions (both public and private), breed more effective service crops adapted to local environments, and develop community breeding strategies in which multiple species are bred together (i.e., symbionts + plants, consociated crops; Denison, 2015).

When considering available knowledge and technologies currently at farmers' reach, service crops appear as one of the preferred tools because they are relatively easy to implement without a thorough structural reconfiguration of the farming system. Their benefits and the knowledge available on their management have already been highlighted, as have also the needs for breeding strategies aiming at increasing their adaptability and performance (cf. section Multifunctional Service Crops). But including service plants or multiple cropping designs such as strip- or intercropping requires new technologies, especially in terms of mechanization, able to cope with the greater complexity inherent to multi-species systems at higher scales.

A key pathway to support the transition to agroecology in large scale farming is the management of carbon, nutrient, and water cycles beyond the scale of the agricultural plot (**Figure 5**). This is nowadays referred to as *circular agriculture* (Hoes et al., 2018), or the integration of crop and livestock systems through biomass transfers at different scales, from single farms to landscapes and regions. The differences between circular agriculture, and integration of crop-livestock systems at farm scale proposed in agroecological systems (e.g., Botreau et al., 2014), are hard to see. Whenever possible, integrating crops and livestock within the same production systems has a number of advantages as it reduces the need for transport and/or processing of bulky biomass, facilitates the rotation between annual crops and pastures over time, opens opportunities for the economic utilization of multi-purpose service plants, incentivizing their adoption by farmers, promotes nutrient recycling within the farm and a diversification of land uses, with more opportunities for ecosystem service provision at landscape level, especially when wetland or forest patches are used as grazing units. The latter point takes us to the next domain in our research agenda, the identification of strategies and spatio-temporal arrangements to share the agricultural landscape with nature.

The interspacing of non-agricultural patches that are co-beneficial in terms of supporting production (e.g., pollinators, natural enemies, flow regulation, etc.) and multiple other ecosystem services can render agriculture more stable, less risky, and less dependent on external inputs (e.g., MacFadyen et al., 2012; Kristensen, 2016; Modernel et al., 2016; Douglas and Landis, 2017; Geneletti et al., 2018; Maldonado et al., 2019).

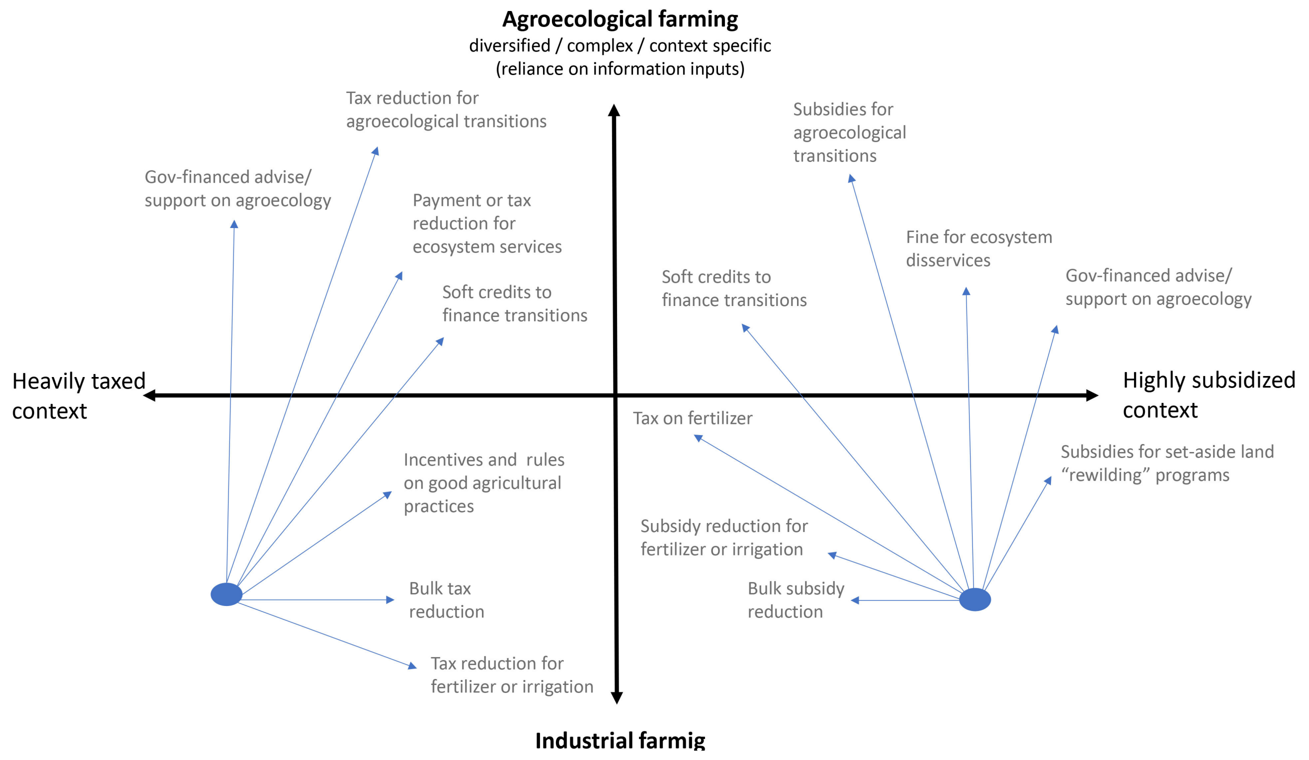

FIGURE 4 | Possible net effects of several policy and financial mechanisms on the likelihood of large-scale farming systems to transition to agroecological farming from their current industrial farming practices. Blue circles indicate the approximate position of average farming systems nowadays, in both heavily taxed and highly subsidized contexts and blue arrows their expected trajectories toward agroecological farming.

The last domain of research we see as fundamental to support agroecological transitions is the co-innovation with farmers, value chains and policy makers to develop new technologies, markets and policy environments that are more conducive for alternative farming. While co-innovation between farmers and researchers has seen much progress in the last decade (e.g., Lacombe et al., 2018), organizational innovations with higher scale actors have been less common (Duru et al., 2015). This domain may develop in parallel with a redirection of taxes and subsidies to stimulate all the above interventions. The level of complexity of the system changes required in agroecological transitions may be also a constraint for some farmers to be able to select and adapt the technologies just by themselves. Collective action, sharing, and co-innovation is often needed.

In innovation systems thinking, innovation is seen as an interactive, non-linear process resulting from the interaction between heterogeneous actors and emerging technological and institutional change (Fagerberg, 2009). Formal agronomic research is an important part of this interactive picture (Sumberg et al., 2012). In the context of innovation platforms (cf. learning centers, e.g., Tittonell et al., 2012) researchers, resource users such as farmers or herders, and other stakeholders come together not just to share their previous knowledge, but to design, experiment, discuss results, make decisions, engage in debate, raise new questions, etc., in a way that allows them to learn together and co-construct new knowledge. The new, emerging mental frames form the basis for more creative and collective solutions. We refer to this collective process as co-innovation or co-design (Dogliotti et al., 2014). Involvement of farmers, extension agents and researchers is essential to develop innovative agroecological systems as well as and innovative advice tools and decision support methods to foster shared learning (e.g., Luedeling and Shepherd, 2016).

Although not explicitly outlined in the rather agronomy-focused research agenda presented here, a number of research questions emerge on the most effective ways to design and organize participation, learning and communication within innovation platforms across different socio-cultural settings and production systems (e.g., Berthet et al., 2018). Context-specific system innovation tools may also be necessary to anchor local innovations with the potential to deliver global scale solutions, as a pre-requisite to their out-scaling (Tittonell et al., 2016). A long-lasting example of bottom-up innovation platforms in the context of large-scale agriculture are the CREA farmer groups in Argentina and Uruguay (CREA: Regional Consortia for Agricultural Experimentation). Emerged in 1957 as a spontaneous organization of a group of farmers (https://www.crea.org.ar/historia) to experiment and learn together, they soon disseminated the idea to other regions and created a national association of regional consortia. Today, they count some 2,000 private farmers organized in 208 regional co-innovation groups that support knowledge development, testing and evaluation

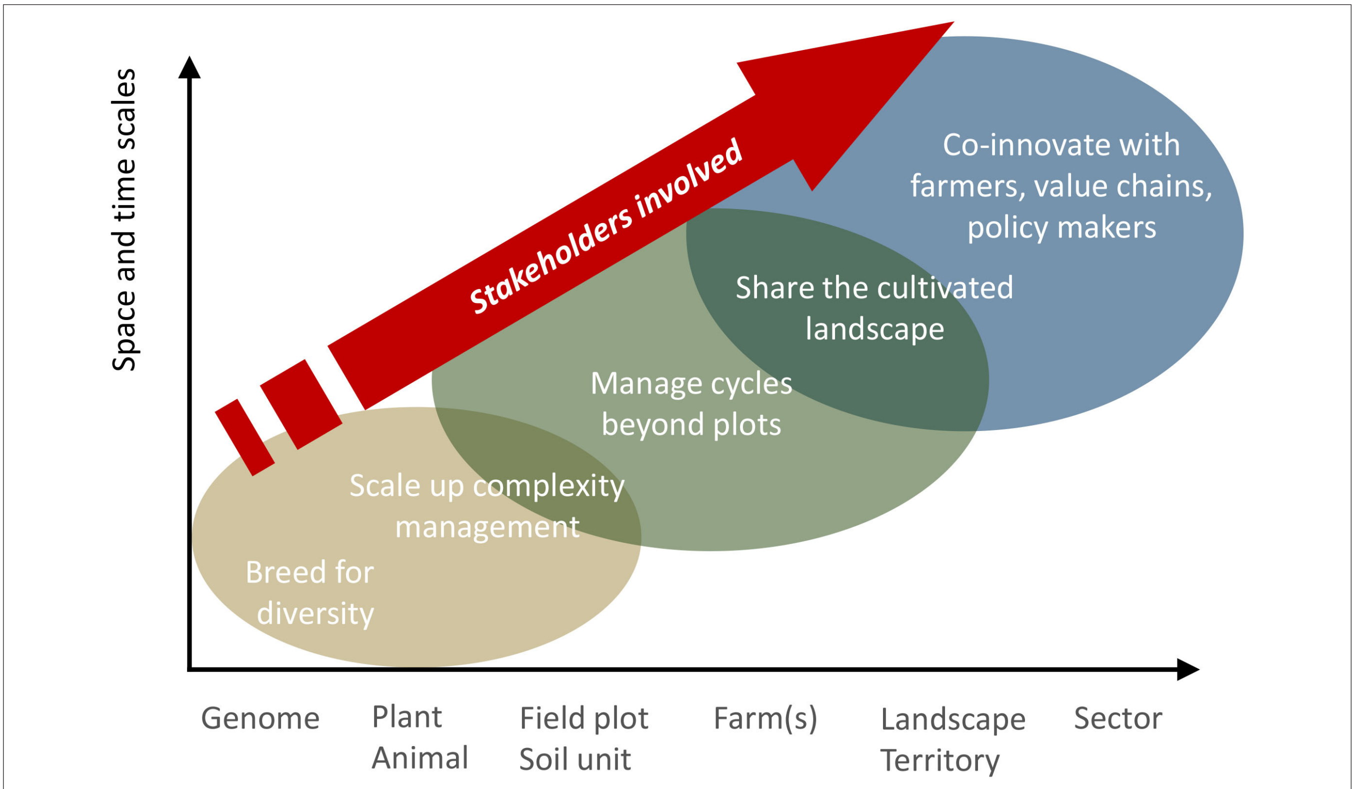

FIGURE 5 | Five major domains defining a research agenda to support agroecological transitions at different levels of integration. At higher levels of integration from genome to sector the number and complexity of stakeholders involved in the process increase.

of technologies and practices, relying on strong links with the academia. Their success and long-standing experience have been often the object of research studies from the domain of social science, knowledge systems and organizations (e.g., Peirano, 2010; Pacín and Oesterheld, 2014). Although the activities of the CREA groups have been to date far from promoting any form of agroecological transitions in large scale farming, their experience, their horizontal, and context-specific nature, plus their demonstrated adaptive capacity over time make them a potentially interesting platform to launch a wide agroecological transition program in large scale farming.

Down to Earth

Agroecology is defined by principles, not by a set of practices (Tittonell, 2020). This is why it becomes so difficult to decide to what extent any farming system is an agroecological system, or at which point in the transition it sits, or what set of practices needs to be implemented for a system to become agroecological, etc. (FAO, 2019). These are common questions among farmers and agronomists, but also among scientists and policy makers who often wonder what options are readily available to engage in a transition. Far from being universally applicable, specific practical recommendations for the transition to agroecology should be designed considering the type of farming system, its context, and the starting point in the transition. This is illustrated in **Table 1** for arable agriculture, particularly large-scale grain production (cereal, pulses, and oil seed crops) in the two contrasting contexts of governmental interventions described earlier, taxes, and subsidies. Management measures for the transition to agroecology in these cases are largely identified in response to the currently most pressing problems associated with industrial agriculture in each context. The list is not exhaustive, and excludes more transformative measures such as integrating livestock in the system, switching from tillage to conservation agriculture, or integrating trees as part of an agroforestry strategy. Such transformative measures would require a thorough redesign of the agricultural system, even re-training farmers and advisors, in parallel with a redesign of associated value chains and sectoral policies (cf. the co-innovation domain in **Figure 5**). Let us not dream too wildly: in most industrial agricultural settings a transition to agroecology, if any, is likely to be gradual, partial, and generally slow.

From the general measures illustrated for arable farming in **Table 1**, a number of finer-grain agronomic and ecological questions remain to be addressed to support agroecology. For example, through *ad-hoc* consultation with farmers, fellow researches, and field agronomists we identified at least 20 fine-grain research questions that we present here:

1. How do above- and below-ground species interact to provide multiple ecosystem services?
2. How many supportive and regulating species are needed and which ones?

TABLE 1 | An illustration of possible measures to transition from current industrial to agroecological intensification in arable agriculture (grain production).

Context	Starting point (industrial farming)	Toward agroecology
Heavily taxed agriculture	• Sub-utilization of rainfall (flooding) • High herbicide use and resistant weeds • Soil erosion and nutrient mining • GHG emissions dominated by soils C losses	• Make full use of rainfall through increased annual soil cover (crops, pastures, trees) • Replace herbicides with service crops • Restore N with biological fixation • Strategic P fertilization and recycling • Recover soil C levels
Highly subsidized agriculture	• Overutilization of rainfall + irrigation (aquifer exhaustion) • High insecticide and fungicide use • Over fertilization • GHG emissions dominated by energy use and N losses	• Restore hydrological fluxes • Replace insecticides and fungicides with diversity and ecosystem services • Recover fertilizer excess with service crops and buffer strips • Reduce energy and fertilizer use

3. Is it possible to improve not only yields but services as well through breeding and selection?
4. Under what circumstances does biodiversity improve crop yield, crop quality and yield/quality stability?
5. To what degree can ecosystem services replace, complement, or interact synergistically with agricultural inputs to achieve resilient and productive farming?
6. What are the impacts of the reduction of feeding resources for beneficial organisms resulting from herbicide use?
7. What are the impacts on pests and beneficial arthropods of long-term exposures to sub-lethal concentrations of different agro-chemicals?
8. How much area of natural or semi-natural habitat is needed within a farm or a landscape?
9. How should these areas be distributed across the landscape? What is the minimum area required?
10. Which variables should be measured for habitat quality?
11. How much soil organic matter is needed in different cropping systems?
12. What fractions of soil organic matter are strategic to protect or restore in each case?
13. Can DNA-extraction based methods for soil biodiversity identification be used as decision support indicators in soil management?
14. How does plant diversity affect water cycles?
15. What mix of annual crops and perennials is needed?
16. How can local practices complement or interact synergistically when integrated into landscape design?
17. What is the potential productivity boundary of agroecological livestock system with different levels of external inputs?
18. How can ecosystem services and other externalities of farming systems be effectively incorporated into decision making?
19. How effective are different approaches to training and skills development in delivering agroecology?
20. How best to quantify tradeoffs between economic viability, biodiversity conservation and ecosystem service provision in agricultural landscapes?

Intensive agriculture is not only affecting biodiversity within its own fields itself, but also in neighboring nature areas, e.g., through nitrogen emissions, pesticide losses, lowering groundwater tables for agriculture (e.g., Hallmann et al., 2017). In the Netherlands, for example, export-oriented horticulture, agriculture, and livestock systems form an important land claim: 0.7% of all households in the country are farmers, but together they use 54% of the land surface (2019). The mounting evidence on such impacts are a strong argument against land sparing approaches for nature conservation. More insight is needed on the relation between intensive agriculture and neighboring nature areas, particularly in the context of Western Europe where both land uses coexist within single landscapes. At which scale can these be in a mosaic? What is the scale of the checkerboard necessary for biodiversity in nature areas to be spared from the impact of intensive farming and still survive? Also, if we were to include a third curve in **Figure 1** to represent natural capital or ecosystem services, we would likely draw an exponential decline indicating loss of biodiversity as input intensification increases. A classical tradeoff. However, we think there is room for smart agroecological interventions that would render the relationship between profit and nature synergistic, allowing for high economic productivity and biodiversity conservation (e.g., Modernel et al., 2018; El Mujtar et al., 2019; Pinillos et al., 2020). In this sense, agroecology supports land sharing approaches to conservation, due to the co-benefits that can be expected from greater biodiversity and ecosystem services.

Yet addressing each one of these questions without embedding them into broader strategies that are context-aware (e.g., **Table 1**) and integrative across scales and levels of organization (e.g., **Figure 5**) would be of little use. In this regard, rooting convergent avenues of agroecological research and innovation at the core of each large-scale farming belt of the world is critical, since knowledge gains from one region are unlikely to get easily transferred to another as it may happen with many industrial agriculture technologies. Also critical is the development of knowledge co-production schemes that are based from their early stage on real life large-size farms. Otherwise, unrealistic promises derived from "boutique" demonstration plots may create more frustration than transformation. Agroforestry initiatives offer a reminder in this sense, with many ecological benefits well-documented in experimental settings for decades, but management systems and business models for large-scale, commercial implementation being still rare (but see Duru et al., 2015).

Beyond Profits

Although the models presented in **Figures 1**, **2** to illustrate intensification pathways assume that large scale farmers are generally gross income maximisers, this is obviously a simplification, as in reality farmers tend to also maximize gross margins and profits. However, economic profit is not the main driver of technology choice among large scale farmers. Socio-cultural factors, such as being perceived as modern farmers that attain high productivity per unit land or animal, or use the latest technologies available is also an important motivation to select intensification means and levels (Dessart et al., 2019). Particularly in highly subsidized systems, farmers tend to pursue the highest possible productivity levels fueled also by the processing sector and by an aggressive commercial push by input and technology suppliers (Levidow et al., 2014).

A similar picture can be seen in heavily taxed contexts, although the economic failure or risk of high input intensification schemes is often attributed, by farmers and other sectoral actors, to the tax burden (OECD, 2019). A comparison between Argentina and Uruguay, however, may indicate otherwise. While the agrarian structure, land use and agricultural practices are quite similar in both countries, public policies with regards to agriculture differ broadly. Tax policies impose a much heavier burden on Argentinian farmers (export tax of 30% for soybean), and although many claim that the economic failure of high input agriculture is due to the government tax policy, the experience in Uruguay where the taxes are much lower shows exactly the same pattern of economic risks, failure and consequent land concentration associated with the expansion of large scale agriculture.

A controversial point about agroecological transitions is their possible impact on labor requirements, especially when several practices for landscape restoration or agroecological management are not yet mechanizable to date. Progress in the fields of robotics, big data, sophisticated precision agriculture or automation is fast and promising, and represents an opportunity when combined with the other sources of knowledge mobilized in agroecology (HLPE, 2019). Labor is still seen as a high cost by farmers, and it may be even seen as rather prohibitive in certain contexts and production systems such as those of Western Europe. Current labor requirements in agriculture range widely across the world, from e.g., 0.004 h Tn^{-1} grain in Argentina, to 0.010 h Tn^{-1} in France or 0.060 h Tn^{-1} in Brazil. Yet unemployment is a major concern affecting livelihoods all over the world. Biodiversity-intensive landscapes can provide more employment in a real economy. A global study using country-level agricultural and socio-economic data showed that countries where crop diversity increased also supported more agricultural jobs (Garibaldi and Pérez-Méndez, 2019). Such effects were independent of differences among countries in the size of the agricultural sector, fertilizer use, crop yields, socio-economic development or economic growth. Moreover, the study found no evidence that the jobs lost in the rural areas were incorporated into other sectors of the economy. Thus, there is evidence for a positive link between two of the United Nations Sustainable Development Goals (SDGs), in the sense that enhancing crop diversity (SDG 2) can also contribute to improving employment rates (SDG 8).

Transforming this labor demand into attractive jobs and livelihoods in large-scale farming contexts will still remain as a challenge that calls for integrating agroecological innovation and social programs. Here again, co-innovation in policies, incentives and regulations are urgently needed to make this shift both viable and attractive to large scale farmers and society as a whole.

CONCLUSIONS

A broad transition to agroecology in large-scale farming across the diverse set of contexts in which it operates will generate returns on four capitals (www.commonland.com): on social capital, by creating jobs, education, business, and security; on natural capital, by restoring biodiversity, soil, water quality and carbon; on financial capital, by realizing long-term sustainable profit: and on inspiration (being a sort of emotional or psychological capital) by giving hope and a sense of purpose to people. Biodiverse farming, as proposed through agroecology, can create more jobs in rural areas, restore biodiversity and ecosystem services, and renew inspiration among large-scale farmers, reduce risks of economic failure in farm business models and provide long term stability (*NB*: the authors have not yet encounter cases in their practice in which farmers who transitioned to agroecology went bankrupt or failed economically; the opposite was often observed: bankrupt or fatigued industrial farmers that moved toward agroecology).

But knowledge gaps remain, at both practical and theoretical levels, to inform real life strategies for the transition of large-scale farming to agroecology. We identified five domains of research that need to be prioritized to foster this agenda:

- Breeding for diversity;
- Scaling up complexity management;
- Managing cycles beyond fields and farms;
- Sharing the cultivated landscape;
- Co-innovating with farmers, value chains and policy makers.

The figures and models used in this paper to describe the current situations of large-scale farming present unidirectional developments. In reality, however, large scale farming landscapes are shaped by several simultaneous drivers—topography being not a minor one—that result in rather homogeneous but not identical situations on each single farm or landscape. We argue that optimum economic productivity does not necessarily occur at the balanced resource use level of intensification, as it may be higher or lower depending on the context. Yet we do know that subsidies will push input intensification and overuse of local resources, while taxes tend to have the opposite effect. Thus, at some point, these instruments may contribute to tune optimum resource use, albeit in a poorly targeted way. Incentives that operate more directly on critical inputs and impacts would be more desirable. For example, by redirecting agricultural tax revenues to restoring soil phosphorus in South America, or through subsidies applied specifically to farmers that cut fertilization or irrigation inputs in Western Europe. A step further would be to tune taxes or subsidies based on the specific incorporation of agroecology's high "intellectual" inputs in the form of landscape complexity management, crop diversity, co-innovation, etc. Yet we see the tuning of taxes and subsidies as a necessary but not sufficient condition to promote transitions to agroecology, which will also require the engagement of other actors along a value chain, including consumers.

Large scale farmers are not necessarily happy in their current situation. They are seen as responsible for environmental degradation while often complaining that they have to spend more time filling in papers than running around on their tractors or in the field with their animals. No doubt that under such circumstances, in both taxed and subsidized agricultural contexts, the average age of large-scale farmers is reaching 60 years old. We hope agroecology can set the scene for a renewed impetus in large scale farming, to attract the youth and its innovative capacity, to foster clean technological innovation, and to promote a new generation of large-scale farmers that take pride in contributing to feeding the world while preserving the planet.

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

PT led the writing process. GP, LG, SD, HO, and EJ contributed text and discussed the different sections. All authors contributed to the article and approved the submitted version.

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REFERENCES

Albicette, M. M., Leoni, C., Ruggia, A., Scarlato, S., Blumetto, O., Albín, A., et al. (2017). Co-innovation in family-farming livestock systems in Rocha, uruguay: a 3-year learning process. *Outlook Agric.* 46, 92–98. doi: 10.1177/0030727017707407

Altesor, A., Oesterheld, M., Leoni, E., Lezama, F., and Rodriguez, C. (2005). Effect of grazing n community structure and productivity of a uruguayan grassland. *Plant Ecol.* 179, 83–91. doi: 10.1007/s11258-004-5800-5

Anderson, C., Bruil, J., Chappell, M., Jahi, K., Csilla, P., and Michel, P. P. (2019). From transition to domains of transformation: getting to sustainable and just food systems through agroecology. *Sustainability* 11:5272. doi: 10.3390/su11195272

Basche, A., and DeLonge, M. (2017). The impact of continuous living cover on soil hydrologic properties: a meta-analysis. *Soil Sci. Soc. Am. J.* 81, 1179–1190. doi: 10.2136/sssaj2017.03.0077

Batáry, P., Dicks, L. V., Kleijn, D., and Sutherland, W. J. (2015). The role of agri-environment schemes in conservation and environmental management. *Conserv. Biol.* 29, 1006–1016. doi: 10.1111/cobi.12536

Berthet, E. T., Hickey, G. M., Klerkx, L. (2018). Opening design and innovation processes in agriculture: insights from design and management sciences and future directions. *Agric. Syst.* 165, 111–115 doi: 10.1016/j.agsy.2018.06.004

Bilenca, D., and Miñarro, F. (2004). *Identificación de Áreas Valiosas de Pastizal (AVPs) en las Pampas y Cam- pos de Argentina, Uruguay y sur de Brasil*. Buenos Aires: Fundación Vida Silvestre Argentina, 320.

Bolsa de Cereales (2020). *Estado y Condicion de Cultivos.* Buenos Aires: Bolsa de Cereales.

Botreau, R., Farruggia, A., Martin, B., Pomiès, D., and Dumont, B. (2014). Towards an agroecological assessment of dairy systems: proposal for a set of criteria suited to mountain farming. *Animal* 8, 1349–1360. doi: 10.1017/S1751731114000925

Brummer, E. C., Barber, W. T., Collier, S. M., Cox, T. S., Johnson, R., Murray, S. C., et al. (2011). Plant breeding for harmony between agriculture and the environment. *Front. Ecol. Environ.* 9, 561–568. doi: 10.1890/100225

Cardinale, B. J., Wright, J. P., Cadotte, M. W., Carroll, I. T., Hector, A., Srivastava, D. S., et al. (2007). Impacts of plant diversity on biomass production increase through time because of species complementarity. *Proc. Natl. Acad. Sci. U.S.A.* 104, 18123–18128 doi: 10.1073/pnas.0709069104

Carriquiry, M., Espasandin, A., Astessiano, A., Casal, A., Claramunt, M., Do Carmo, M., et al. (2012). La cría vacuna sobre campo nativo: Un enfoque de investigación jerárquico para mejorar su productividad y sostenibilidad. *Vet.* 48, 41–48.

Carvalho, P., Nabinger, C., Lemaire, G., Genro, T. (2011). "Challenges and opportunities for livestock production in natural pastures: the case of Brazilian Pampa Biome," in *Diverse Rangelands for a Sustainable Society, IX International Rangeland Congress*, eds S. Feldman, G. Oliva, and M. Sacido (Rosario), IX–XV.

Cole, L. J., Stockan, J., and Helliwell, R. (2020). Managing riparian buffer strips to optimise ecosystem services: a review. *Agric. Ecosyst. Environ.* 296:106891. doi: 10.1016/j.agee.2020.106891

Dainese, M., Martin, E. A., Aizen, M. A., Albrecht, M., Bartomeus, I., Bommarco, R., et al. (2019). A global synthesis reveals biodiversity-mediated benefits for crop production. *Sci. Adv.* 5:eaaax0121. doi: 10.1126/sciadv.aax0121

de Haas, B. R., Hoekstra, N. J., van der Schoot, J. R., Visser, E. J. W., de Kroon, H., and van Eekeren, N. (2019). Combining agro-ecological functions in grass-clover mixtures. *AIMS Agric. Food*. 4, 547–567. doi: 10.3934/agrfood.2019.3.547

Denison, R. F. (2015). "Chapter 9: A darwinian perspective on improving nitrogen-fixation efficiency of legume crops and forages," in *Crop Physiology, 2nd edn,* eds V. O. Sadras and D. F. Calderini (Amsterdam: Academic Press), 207–222. doi: 10.1016/B978-0-12-417104-6.00009-1

Dessart, F. J., Barreiro-Hurlé, J., and van Bavel, R. (2019). Behavioural factors affecting the adoption of sustainable farming practices: a policy-oriented review. *Eur. Rev. Agric. Econ*. 46, 417–471. doi: 10.1093/erae/jbz019

Deverre, C., and de Sainte-Marie, C. (2008). L'écologisation de la politique agricole européenne. Verdissement ou refondation des systèmes agro-alimentaires? *Anglais* 89, 83–104. doi: 10.22004/ag.econ.207798

Ditzler, L. van Apeldoorn, D. F., Schulte, R. P. O., Tittonell, P., and Rossing, W. A. H. (2020). Redefining the field to mobilize three-dimensional diversity and ecosystem services on the arable farm. *Euro. J. Agron*. 177:126197. doi: 10.1016/j.eja.2020.126197

Do Carmo, M., Cardozo, G. A., Jaurena, M. A., and Soca, P. M. (2018). Demonstrating control of forage allowance for beef cattle grazing Campos grassland in Uruguay to improve system productivity. *Trop. Grasslands Forrajes Trop.* 7:35–47. doi: 10.17138/tgft(7)35-47

Do Carmo, M., Claramunt, M., and Soca, P. (2016). Animal energetics in extensive grazing systems: rationality and results of research models to improve energy efficiency of beef cow-calf grazing Campos systems. *J. Anim. Sci*. 94, 84–92. doi: 10.2527/jas2016-0596

Dogliotti, S., García, M. C., Peluffo, S., Dieste, J. P., Pedemonte, A. J., Bacigalupe, G. F., et al. (2014). Co-innovation of family farm systems: a systems approach to sustainable agriculture. *Agric. Syst*. 126, 76–86. doi: 10.1016/j.agsy.2013.02.009

Dollinger, J., Dagès, C., Bailly, J., Lagacherie, P., and Voltz, M. (2015). Managing ditches for agroecological engineering of landscape. A review. *Agron. Sustain. Dev*. 35, 999–1020. doi: 10.1007/s13593-015-0301-6

Douglas, A., and Landis, D. A. (2017). Designing agricultural landscapes for biodiversity-based ecosystem services. *Basic Appl. Ecol.* 18, 1–12. doi: 10.1016/j.baae.2016.07.005

Dumont, B., Fortun-Lamothe, L., Jouven, M., Thomas, M., and Tichit, M. (2013). Prospects from agroecology and industrial ecology for animal production in the 21st century. *Animal* 7, 1028–1043. doi: 10.1017/S1751731112002418

Duru, M., Therond, O., and Fares, M. (2015). Designing agroecological transitions a review. *Agron. Sustain. Dev*. 35, 1237–1257. doi: 10.1007/s13593-015-0318-x

El Mujtar, N., Muñoz, B., Prack Mc Cormick, M., Pulleman, M., and Tittonell, P. (2019). Role and management of soil biodiversity for food security and nutrition; where do we stand? *Global Food Sec.* 20, 132–144. doi: 10.1016/j.gfs.2019.01.007

Elzen, B., Augustyn, A. M., Barbier, M., and van Mierlo, B. (2017). *Agroecological Transitions: Changes and Breakthroughs in the Making*. Wageningen: Wageningen University & Research. doi: 10.18174/407609

Fagerberg, J. (2009). "Innovation: a guide to the literature," in *The Oxford Handbook of Innovation*, eds J. Fagerberg and D. C. Mowery. doi: 10.1093/oxfordhb/9780199286805.003.0001

FAO (2019). *TAPE Tool for Agroecology Performance Evaluation 2019 - Process of Development and Guidelines for Application*, Test version. Rome: FAO.

Garcia, L., Celette, F., Gary, C., Ripoche, A., Valdés-Gómez, H., and Metay, A. (2018). Management of service crops for the provision of ecosystem services in vineyards: a review. *Agric. Ecosyst. Environ.* 251, 158–170. doi: 10.1016/j.agee.2017.09.030

Garibaldi, L. A., Carvalheiro, L. G., Leonhardt, S. D., Aizen, M. A., Blaauw, B. R., Isaacs, R., et al. (2014). From research to action: enhancing crop yield through wild pollinators. *Front. Ecol. Environ.* 12, 439–447. doi: 10.1890/130330

Garibaldi, L. A., Carvalheiro, L. G., Vaissiere, B. E., Gemmill-Herren, B., Hipolito, J., Freitas, B. M., et al. (2016). Mutually beneficial pollinator diversity and crop yield outcomes in small and large farms. *Science* 351, 388–391. doi: 10.1126/science.aac7287

Garibaldi, L. A., and Pérez-Méndez, N. (2019). Positive outcomes between crop diversity and agricultural employment worldwide. *Ecol. Econ.* 164:106358. doi: 10.1016/j.ecolecon.2019.106358

Geneletti, D., Rocco, S., and Blal Adem, E. (2018). Assessing ecosystem services and biodiversity tradeoffs across agricultural landscapes in a mountain region. *Int. J. Biodiv. Sci. Ecosyst. Serv. Manag.* 14, 188–208. doi: 10.1080/21513732.2018.1526214

Gill, J. A., Langston, R. H. W., Alves, J. A., Atkinson, P. W., Bocher, P., Cidraes Vieira, N., et al. (2007). Contrasting trends in two black-tailed godwit populations: a review of causes and recommendations. *Wader Study Group Bull.* 114, 43–50.

Giménez, R., Mercau, J., Nosetto, M., Páez, R., and Jobbágy, E. (2016). The ecohydrological imprint of deforestation in the semiarid Chaco: insights from the last forest remnants of a highly cultivated landscape. *Hydrol. Process*. 30, 2603–2616. doi: 10.1002/hyp.10901

Graeub, B. E., Chappell, M. J., Wittman, H., Ledermann, S., Kerr, R. B., and Gemmill-Herren, B., (2016). The state of family farms in the world. *World Dev.* 87, 1–15. doi: 10.1016/j.worlddev.2015.05.012

Groot, J. C. J., Cortez-Arriola, J., Rossing, W. A. H., Massiotti, R. D. A., and Tittonell, P. (2016). Capturing agroecosystem vulnerability and resilience. *Sustainability* 8:1206. doi: 10.3390/su8111206

Hallmann, C. A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., et al. (2017). More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PLoS ONE* 12:e0185809. doi: 10.1371/journal.pone.0185809

Helmers, M. J., Zhou, X., Asbjornsen, H., Kolka, R., Tomer, M. D., and Cruse, R. M. (2012). Sediment removal by prairie filter strips in row?cropped ephemeral watersheds. *J. Environ. Qual.* 41, 1531–1539. doi: 10.2134/jeq2011.0473

Hendershot, J. N., Smith, J. R., Anderson, C. B., Letten, A. D., Frishkoff, L. O., Zook, J. R., et al. (2020). Intensive farming drives long-term shifts in avian community composition. *Nature* 579, 393–396. doi: 10.1038/s41586-020-2090-6

HLPE (2019). "Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition," in *A Report by the High Level Panel of Experts (HLPE) on Food Security and Nutrition of the Committee on World Food Security, Rome*.

Hoes, A.-C., Roel, J., van Berkum, S., and Poppe, K. (2018). *Towards Sustainable Food Systems. A Dutch Approach*. Wageningen: Wageningen University.

Holland, J. M., Bianchi, F. J., Entling, M. H., Moonen, A. C., Smith, B. M., and Jeanneret, P., (2016). Structure, function and management of semi-natural habitats for conservation biological control: a review of European studies. *Pest Manag. Sci.* 72, 1638–1651. doi: 10.1002/ps.4318

Hoogsteen, M. J. J., Bakker, E.-J., van Eekeren, N., Tittonell, P. A., Groot, J. C. J., van Ittersum, M. K., et al. (2020). Do grazing systems and species composition affect root biomass and soil organic matter dynamics in temperate grassland swards? *Sustainability* 12:1260. doi: 10.3390/su12031260

Howison, R. A., Piersma, T., Kentie, R., Hooijmeijer, J. C. E. W., and Olff, H. (2018). Quantifying landscape-level land-use intensity patterns through radar-based remote sensing. *J. Appl. Ecol.* 55, 1276–1287. doi: 10.1111/1365-2664.13077

IPBES (2019). *Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*.

Jobbágy, E. G., Nosetto, M. D., Santoni, C. S., and Baldi, G. (2008). El desafío ecohidrológico de las transiciones entre sistemas leñosos y herbáceos en la llanura chaco - pampeana. *Asoc. Argentina Ecol. AsAE. Buenos Aires* 18, 305–322.

Kell, D. B. (2011). Breeding crop plants with deep roots: their role in sustainable carbon, nutrient and water sequestration. *Ann. Bot.* 108, 407–418. doi: 10.1093/aob/mcr175

Kentie, R., Senner, N. R., Hooijmeijer, J. C. E. W., Márquez-Ferrando, R., Figuerola, J., Masero, J. A., et al. (2016). Estimating the size of the dutch breeding population of continental black-tailed godwits from 2007–2015 using resighting data from spring staging sites. *Ardea* 104, 213–225. doi: 10.5253/arde.v104i3.a7

Kleijn, D., Berendse, F., Smit, R., Gilissen, N., Smit, J., Brak, B., et al. (2004). Ecological effectiveness of agri-environment schemes in different agricultural landscapes in the Netherlands. *Conserv. Biol.* 18, 775–786. doi: 10.1111/j.1523-1739.2004.00550.x

Kleijn, D., Bommarco, R., Fijen, T. P. M., Garibaldi, L. A., Potts, S. G., and van der Putten, W. H. (2019). Ecological Intensification: bridging the gap between science and practice. *Trends Ecol. Evol.* 34, 154–166. doi: 10.1016/j.tree.2018.11.002

Koks, B. J., Trierweiler, C., Visser, E. G., Dijkstra, C., and Komdeur, J. (2007). Do voles make agricultural habitat attractive to Montagu's Harrier Circus pygargus? Ibis 149, 575–586.

Kristensen, S. B. P. (2016). Agriculture and landscape interaction—landowners' decision-making and drivers of land use change in rural Europe. *Land Use Policy* 57, 759–763. doi: 10.1016/j.landusepol.2016.05.025

Kuppel, S., Houspanossian, J., Nosetto, M. D., and Jobbagy, E. G. (2015). What does it take to flood the pampas? Lessons from a decade of strong hydrological fluctuations. *Water Resour. Res.* 51, 2937–2950. doi: 10.1002/2015WR016966

Lacombe, C., Couix, N., and Hazard, L. (2018). Designing agroecological farming systems with farmers: a review. *Agric. Syst.* 165, 208–220. doi: 10.1016/j.agsy.2018.06.014

Levidow, L., Pimbert, M., and Vanloqueren, G. (2014). Agroecological research: con- forming—or transforming the dominant agro-food regime? *Agroecol. Sustain. Food Syst*. 38, 1127–1155. doi: 10.1080/21683565.2014.951459

Loconto, A., Marion, D., Moreau, T., Couvet, D., and Dorin, B. (2020). The land sparing – land sharing controversy: tracing the politics of knowledge. *Land Use Policy* 96:103610. doi: 10.1016/j.landusepol.2018.09.014

Lowder, S. K., Sánchez, M. V., and Bertini, R. (2019). Farms, family farms, farmland distribution and farm labour: What do we know today? *FAO Agricultural Development Economics Working Paper 19–08*. Rome: FAO.

Luedeling, E., and Shepherd, K. (2016). Decision-focused agricultural research. *Solut. J.* 7, 46–54.

MacFadyen, S., Cunningham, S. A., Costamagna, A. C., and Schellhorn, N. A. (2012). Managing ecosystem services and biodiversity conservation in agricultural landscapes: are the solutions the same? *J. Appl. Ecol.* 49, 690–694 doi: 10.1111/j.1365-2664.2012.02132.x

Mack, R. N., Simberloff, D., Lonsdale, W. M., Evans, H., Clout, M., and Bazzaz, F. A. (2000). Biotic invasions: causes, epidemiology, global consequences, and control. *Ecol. Appl*. 10, 689–710. doi: 10.1890/1051-0761(2000)010[0689:BICEGC]2.0.CO;2

Maldonado, A. D., Ramos-López, D., Aguilera, P. A. (2019). The role of cultural landscapes in the delivery of provisioning ecosystem services in protected. *Areas Sustain*. 11:2471. doi: 10.3390/su11092471

Martin, E. A., Dainese, M., Clough, Y., Báldi, A., Bommarco, R., Gagic, V., et al. (2019). The interplay of landscape composition and configuration: new pathways to manage functional biodiversity and agroecosystem services across Europe. *Ecol. Lett.* 22, 1083–1094. doi: 10.1111/ele.13265

Mercau, J. L., Jobbagy, E. G., Viglizzo, E., Menendez, A., Di Bella, C., Bert, F., et al. (2013). Sequía e inundación en la hiperllanura pampeana. Una mirada desde el lote al municipio. *Rev. Agron.* 33, 71–77.

Ministére de l'Agriculture and de l'Agroalimentaire et de la Forét (2017). *Rapport Annuel: la Dynamique Agro-Écologique en 2016*. Paris: Ministére de l'Agriculture and de l'Agroalimentaire et de la Forét, 52.

Modernel, P., Dogliotti, S., Alvarez, S., Corbeels, M., Picasso, V., Tittonell, P., et al. (2018). Identification of beef production farms in the Pampas and Campos area that stand out in economic and environmental performance. *Ecol. Indicat.* 89, 755–770. doi: 10.1016/j.ecolind.2018.01.038

Modernel, P., Picasso, V., Do Carmo, M., Rossing, W. A. H., Corbeels, M., Soca, P., et al. (2019). Grazing management for more resilient mixed livestock farming systems on native grasslands of southern South America. *Grass Forage Sci.* 74, 1–14. doi: 10.1111/gfs.12445

Modernel, P., Rossing, W. A. H., Corbeels, M., Dogliotti, S., Picasso, V., and Tittonell, P. (2016). Land use change and ecosystem service provision in Pampas and Campos grasslands of southern South America. *Environ. Res. Lett.* 11:113002. doi: 10.1088/1748-9326/11/11/113002

Nosetto, M. D., Jobbágy, E. G., Brizuela, A. B., Jackson, R. B. (2012). The hydrologic consequences of land cover change in central Argentina. *Agric. Ecosyst. Environ.* 154, 2–11. doi: 10.1016/j.agee.2011.01.008

Nosetto, M. D., Paez, R. A., Ballesteros, S. I., Jobbágy, E. G. (2015). Higher water-table levels and flooding risk under grain vs. livestock production systems in the subhumid plains of the pampas. *Agric. Ecosyst. Environ.* 206, 60–70. doi: 10.1016/j.agee.2015.03.009

OECD (2019). *Agricultural Policies in Argentina*. Trade and Agriculture Directorate Committee For Agriculture, Organisation for Economic Co-operation and Development, TAD/CA(2018)9/FINAL

Overbeck, G. E., Muller, S. C., Fidelis, A., Pfadenhauer, J., Pillar, V. D., Blanco, I. I., et al. (2007). Brazil's neglected biome: the South Brazilian campos perspect. *Plant Ecol. Evol. Syst.* 9, 101–116. doi: 10.1016/j.ppees.2007.07.005

Pacín, F., and Oesterheld, M. (2014). In farm diversity stabilizes return on capital. *Agric. Syst.* 124, 51–59. doi: 10.1016/j.agsy.2013.10.008

Parra, G., Borrás, L., and Gambin, B. L. (2020). Maize long-term genetic progress explains current dominance over sorghum in Argentina. *Eur. J. Agron.* 119:126122. doi: 10.1016/j.eja.2020.126122

Peirano, M. E. (2010). *Sensemaking in Small Farming Stories: Knowledge Creation in Crea Groups in Argentina*. Palmerston North: Massey University.

Phocas, F., Belloc, C., Bidanel, J., Delaby, L., Dourmad, J. Y., Dumont, B., et al. (2016). Review: towards the agroecological management of ruminants, pigs and poultry through the development of sustainable breeding programmes. II. Breeding strategies. *Animal* 10, 1760–1769. doi: 10.1017/S1751731116001051

Picasso, V. D., Modernel, P. D., Becoña, G., Salvo, L., Gutiérrez, L., and Astigarraga, L. (2014). Sustainability of meat production beyond carbon footprint: a synthesis of case studiesfrom grazing systems in Uruguay. *Meat Sci.* 98, 346–354. doi: 10.1016/j.meatsci.2014.07.005

Pinillos, D., Bianchi, F. J. J. A., Poccard-Chapuis, R., Corbeels, M., Tittonell, P., and Schulte, R. P. O. (2020). Understanding landscape multifunctionality in a post-forest frontier: supply and demand of ecosystem services in eastern Amazonia. *Front. Environ. Sci.* 7:206. doi: 10.3389/fenvs.2019.00206

Pinto, P., Long, M. E. F., and Piñeiro, G. (2017). Including cover crops during fallow periods for increasing ecosystem services: is it possible in croplands of Southern South America? *Agric. Ecosyst. Environ.* 248, 48–57. doi: 10.1016/j.agee.2017.07.028

Schipanski, M. E., Barbercheck, M., Douglas, M. R., Finney, D. M., Haider, K., Kaye, J. P., et al. (2014). A framework for evaluating ecosystem services provided by cover crops in agroecosystems. *Agric. Syst.* 125, 12–22. doi: 10.1016/j.agsy.2013.11.004

Schlaich, A. E., Klaassen, R. H. G., Bouten, W., Both, C., and Koks, B. J. (2015). Testing a novel agri-environment scheme based on the ecology of the target species, *Montagu's Harrier Circus pygargus*. *Ibis* 157, 713–721. doi: 10.1111/ibi.12299

Scholberg, J. M. S., Dogliotti, S., Leoni, C., Zotarelli, L., Cherr, C. M., and Rossing, W. A. H. (2010). "Chapter 2: Cover crops for sustainable agrosystems in the Americas," in *Genetic Engineering, Biofertilisation, Soil Quality and Organic Farming,* ed E. Lichtfouse (New York, NY: Sustainable Agriculture Reviews; No. 4), 23–58. doi: 10.1007/978-90-481-8741-6_2

Schulte, L. A., Niemi, J., Helmers, M. J., Liebman, M., Arbuckle, J. G., James, D. E., et al. (2017). Prairie strips improve biodiversity and the delivery of multiple ecosystem services from corn-soybean croplands. *Proc. Natl. Acad. Sci.* 114, 11247–11252. doi: 10.1073/pnas.1620229114

Shunmugam, A. S. K., Kannan, U., Jiang, Y., Daba, K. A., Gorim, L. Y. (2018). Physiology based approaches for breeding of next-generation food legumes. *Plants* 7:72. doi: 10.3390/plants7030072

Stassart, P. M., Crivits, M., Hermesse, J., Tessier, L., Van Damme, J., and Dessein, J. (2018). The generative potential of tensions within belgian agroecology. *Sustainability* 10:2094. doi: 10.3390/su10062094

Sumberg, J., Thompson, J., and Woodhouse, P. (2012). Why agronomy in the developing world has become contentious. Agric. Hum. Values 1–13, doi: 10.1007/s10460-012-9376-8

Tilman, D. (1988). *Plant Strategies and the Dynamics and Structure of Plant Communities*. Princeton, NJ: Princeton University Press. doi: 10.1515/9780691209593

Tittonell, P. (2014). Ecological intensification – sustainable by nature. *Curr. Opin. Environ. Sustain.* 8, 53–61. doi: 10.1016/j.cosust.2014.08.006

Tittonell, P. (2020). Assessing resilience and adaptability in agroecological transitions. *Agric. Syst.* 184:102862. doi: 10.1016/j.agsy.2020.102862

Tittonell, P., Laurens, K., Frederic, B., Félix, G. F., Ruggia, A., van Apeldoorn, D., et al. (2016). Ecological intensification: local innovation to address global challenges. *Sustain. Agric. Rev.* 19, 1–34. doi: 10.1007/978-3-319-26777-7_1

Tittonell, P., Scopel, E., Andrieu, N., Posthumus, H., Mapfumo, P., Corbeels, M., et al. (2012). Agroecology-based aggradation-conservation agriculture (ABACO): targeting innovations to combat soil degradation and food insecurity in semi-arid Africa. *Field Crop Res.* 132, 168–174. doi: 10.1016/j.fcr.2011.12.011

Tittonell. P. (2019). Las transiciones agroecológicas: múltiples escalas, niveles y desafíos. *Rev. FCA UNCUYO* 51, 231–246.

Tsiafouli, M. A., Thébault, E., Sgardelis, S. P., de Ruiter, P. C., van der Putten, W. H., Birkhofer, K., et al. (2015). Intensive agriculture reduces soil biodiversity across Europe. *Global Change Biol.* 21, 973–985. doi: 10.1111/gcb.12752

van der Ploeg, J. (2013). The genesis and further unfolding of farming styles research. *Historische Anthropol.* 20, 427–439. doi: 10.7788/ha.2012.20.3.427

Wayman, S., Kucek, L. K., Mirsky, S. B., Ackroyd, V., Cordeau, S., and Ryan, M. R. (2017). Organic and conventional farmers differ in their perspectives on cover crop use and breeding. *Renew. Agric. Food Syst.* 32, 376–385. doi: 10.1017/S1742170516000338

Weltzien, E., and Christinck, A. (2017). "Chapter 8 - participatory breeding: developing improved and relevant crop varieties with farmers," in *Agricultural Systems, 2nd edn*, eds S. Snapp and B. Pound (Amsterdam: Academic Press), 259–301.

Wezel, A., Goris, M., Bruil, J., Félix, G. F., Peeters, A., Bàrberi, P., et al. (2018). Challenges and actions points to amplify agroecology in Europe. *Sustainability* 10:1598. doi: 10.3390/su10051598

WWF (2018). *Living Planet Report – 2018: Aiming Higher*, eds M. Grooten and R. E. A. Almond.

WWF (2020). *Living Planet Report 2020 - Bending the Curve of Biodiversity Loss*, eds R. E. A. Almond, M. Grooten, and T. Petersen.

Zulauf, C., and Brown, B. (2019). "Cover crops, 2017 US census of agriculture," in *Farmdoc Daily (9):135, Department of Agricultural and Consumer Economics* (Champaign, IL: University of Illinois at Urbana).

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Yuck! Plural Valuation of Constructed Wetland Maintenance for Decentralized Wastewater Treatment in Rural India

Claire N. Friedrichsen[1*†], *Martha C. Monroe*[2], *Samira H. Daroub*[3] and *Suhas P. Wani*[1]

[1] Development Center Asia, International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India, [2] Human Dimensions of Natural Resources Lab, School of Forestry and Conservation, University of Florida, Gainesville, FL, United States, [3] Everglades Research and Education Center, Department of Soil and Water Sciences, University of Florida, Belle Glade, FL, United States

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Singapore, in collaboration with
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***Correspondence:**
Claire N. Friedrichsen
clairef@uidaho.edu

†Present address:
Claire N. Friedrichsen,
Transformational Agro-Ecosystems
Science Team, Long-Term
Agro-Ecosystems Research Network,
Department of Natural Resources and
Society, University of Idaho, Moscow,
ID, United States

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In 2012, an estimated 50% of rural households in India had a system of drainage for moving wastewater away from their homes, but 0.0% have access to safe, reuseable, treated wastewater. Constructed wetlands can provide decentralized wastewater treatment for rural villages and lead to multiple benefits, such as reusable water, reduced disease, and decreased environmental pollution. However, the maintenance of decentralized wastewater technologies is poorly understood. We used a case study design across four communities and six constructed wetlands to understand the social and cultural variables impacting the maintenance of constructed wetlands for decentralized wastewater treatment to provide agricultural irrigation water. Semi-structured interviews ($n = 39$) and focus groups ($n = 4$) were conducted with people from Telangana and Karnataka, India. Interviewees were classed into four groups: (1) Scientists, (2) Farmers, (3) Privileged Community Members, and (4) Socially Disadvantaged Community members. Inductive, constant comparison qualitative data analysis was used to develop a model for explaining the existing practice of wetland maintenance. Three themes emerged from the data: mental models of constructed wetland maintenance show plural valuation of ecosystem services, yuck as a leverage point for decreasing social cohesion in the community, and recommendations for improving maintenance through human-centered design. Based on the results, we propose a model for understanding how to incorporate the plural valuation of ecosystem services provided by constructed wetlands and human-centered design to support long-term adoption and maintenance of decentralized wastewater treatment technologies.

Keywords: water reuse, perception, agroecology, adoption, public health, WASH, irrigation, caste (untouchability)

INTRODUCTION

Over 1.3 billion individuals live in India. Wastewater (WW) from hundreds of millions of individuals goes untreated and is released back into the environment, leading to an increased incidence of disease and environmental pollution. Decentralized WW treatment (DWT) is one reasonable option for some rural communities. Yet, there is no widespread adoption despite many different available technologies and a significant amount of capital devoted to providing a solution.

Without proper water, sanitation, and hygiene (WASH), developing countries face limited growth in their Gross Domestic Product, high child mortality, limited life spans, and stunting in children (LoPalo et al., 2019). Historically, WASH programs focused on water supply and behavioral sanitation practices, and little research looked at how communities manage downstream WASH infrastructure. Wastewater treatment is an essential component of WASH for minimizing exposure to pathogens.

Constructed wetlands (CWs) are a proposed technology for water treatment and are widely used for primary and secondary WW treatment (Vymazal, 2011; Starkl et al., 2015). CWs are often regarded as a green solution for WW treatment for their relative simplicity, reliance on natural systems, green space, habitat for wildlife, limited energy requirement, and low level of technical skills needed for maintenance (Kumar and Dutta, 2019). Constructed wetlands require regular and reactionary maintenance to ensure that the physical, chemical, and biological treatment mechanisms continue to function effectively for delivering high-quality treated outflow (Werellagama and Karunaratne, 2011). The maintenance activities depend upon the plants' growing conditions inside of the CWs, the water quality of the inflow, WASH conditions of the community, and storm water related reactionary maintenance. Little is known about the process and impacting variables that affect long-term adoption and maintenance of CWs in rural communities.

This research answers the call by Desai et al. (2015) to provide in-depth case studies of the maintenance of infrastructure in India and of Schouten and Moriarty (2003) to provide a critical evaluation of existing community water management programs and insight into improving maintenance and community management of water systems in developing countries. This research also helps better understand the impacts of power and plural valuation, divergent perceptions of how nature benefits human well-being, and ecosystem services within community development (Jacobs et al., 2020). The perception differences of how the various stakeholders perceive the ecosystem services of CWs for WW treatment have not been explored to date. The studies herein examine the challenges for long-term maintenance of six CWs in South Central, India. This research explores the nexus of the existing theories and knowledge of agricultural WW reuse, maintenance of decentralized WW systems, and community-based water management.

Friedrichsen et al. (2020) describe the gaps in communication related to ecological knowledge, maintenance, and monitoring of constructed wastewater wetlands, but does not address the socio/cultural barriers to the maintenance of constructed wetlands. The objectives of this study are, therefore, to investigate what factors limit community maintenance and how these interrelate. The yuck factor and other plural values of CWs need to be incorporated into the design and implementation process of CWs to facilitate sustained maintenance. The findings enabled us to suggest recommendations for the design and dissemination process of CWs as community development projects for enhancing community WW treatment. Three key research questions are addressed in this investigation: (1) How does the plural valuation of ecosystem services impact maintenance of CWs for DWT? (2) How does the yuck factor influence social cohesion and plural valuation of ecosystem services of CWs? (3) How can the design of CWs be human-centered to account for the plural valuation of ecosystems?

While some studies have explored engineering and water quality aspects of CWs and DWT, few develop a social understanding of perspectives and maintenance of DWT. Due to the degree of personal contact and maintenance required, the adoption of decentralized units differs significantly from centralized units due to the yuck factor (Mankad and Tapsuwan, 2011). However, it is not clear how these differences extend to the adoption of DWT for agricultural irrigation or how they affect maintenance behavior of predictive maintenance models (Devitt et al., 2016). The psychological socio-cultural response to WW has often been characterized in the literature as the yuck factor (Mankad and Tapsuwan, 2011) or attributed to religious contextual differences (Saad et al., 2017). The yuck factor is the immediate emotional disgust or repugnance that causes aversion. The yuck factor is culturally taught (Schmidt, 2008) and disgust can be caused by several factors, such as violation of morality including ideas of holiness and purity, aversion of pathogens, or sexual defilement (Rozin et al., 1999; Rozin, 2015).

Case studies across the globe provide insight into barriers to maintenance and why CWs may fail. Across four CWs in India, barriers to maintenance included lack of perceived ownership, lack of effective institutional structure to raise maintenance funds, lack of equitable access to valued output (e.g., harvested, composted aquatic vegetation), and lack of finances (Kumar et al., 2016). In Thailand, the lack of a key person to take responsibility for maintenance, lack of skill in maintaining effective community engagement and participation, ineffective regulation of the CW, high rate of construction error, and lack of perceived value of the generated services (i.e., wastewater treatment, composted sludge, etc.) provided by the CW all limited maintenance (Laugesen et al., 2010a; Brix et al., 2011). In Latin America, Gauss (2008) observed the maintenance of 10 CWs, identifying lack of access to consistent influent water flow, ownership, community organization, equipment, community involvement in planning, appropriate skill level, accounting for maintenance in the planning process, and limited financial resources as barriers to maintenance of CWs (Gauss, 2008). In a meta-analysis of sanitation infrastructural project case studies across India, Mexico, and South Africa, the lack of appropriate, effective, long-term engagement of the community from the initial planning through maintenance was identified as the mechanism leading to failure of the systems (Starkl et al., 2013b).

However, little research has examined how the yuck factor has impacted maintenance.

The governance of natural resources reflects the most powerful stakeholders' values and their cultural worldview (Colvin et al., 2015; Suhardiman et al., 2019). All people value fairness and purity and seek to avoid harm, but how those values are applied by different groups result in priority differences (Haidt, 2007). This can impact behavior and lead stakeholders to support different environmental governance policies (Stern, 2000). Several lines of research explore this work, including the plural valuation of ecosystem services (Arias-Arévalo et al., 2018; Jacobs et al., 2020), nature's contribution to people (NCP) (Díaz et al., 2018), and critical theory of environmental social justice. Values are important determinants of behavior, and other theories explain how values impact the way individuals make decisions about environmental behaviors (Stern et al., 1999), how values impact the governance of landscapes (Schulz et al., 2018, 2019), and how to account for trade-offs across the relational, intrinsic, and instrumental values in ecosystem management policy (Ellis et al., 2019).

However, it is particularly difficult to articulate the values of an ecosystem service and incorporate them into policymaking, especially when their derived value can attenuate the social division of socially disadvantaged communities from those in power, influencing intrinsic and intangible dimensions of well-being (Wegner and Pascual, 2011). There is a substantial impact on group identity and political power that influences how various stakeholders support particular environmental policies (Kahan, 2010). Decisions in the political sphere may be based on moral foundations that appeal to the most dominant group (Haidt, 2007).

Plural valuation of ecosystem services recognizes that different stakeholders perceive varying values, connect ecosystem services to well-being, and recognize power dynamics between stakeholders perpetuate inequality and conflict related to environmental management (Arias-Arévalo et al., 2018; Jacobs et al., 2020; Zafra-Calvo et al., 2020). If not accounted for in environmental management, plural valuation of ecosystem services may contribute to social division eroding a community's social cohesion (Berbés-Blázquez et al., 2016). For example, in the United States, a wastewater reuse project was plagued by power dynamics and discrimination (Lejano and Leong, 2012). Social cohesion is the "nature and extent of social and economic divisions within society" (Easterly et al., 2006). Social cohesion is strongest when there are limited leverage points where divisions and inequality can be aggravated, but instead, the community embraces and is empowered by its diversity to improve wellbeing (Easterly et al., 2006). Without social cohesion, there is limited capacity for the community to have effective communication channels for providing feedback for maintenance. If the ecosystem is ignored, community development programs may not function as intended and may even negatively impact environmental management (Zafra-Calvo et al., 2020).

The caste system was a type of social order in India before British colonization and was exacerbated by colonial policy. It has led to widespread discrimination and marginalization, reducing social cohesion. The concepts of purity and pollution imply that garbage, human feces, and wastewater are polluting elements, and individuals who work with those resources are thusly polluted (Gupta et al., 2016; Doron, 2018). Some socially disadvantaged individuals and groups seeking to improve their social hierarchy do not want to be associated with their historical occupation and do not want employment in these sectors. Socially disadvantaged community members may include scheduled castes, scheduled tribes, and other backward castes (Gupta, 2005). Additionally, individuals of higher castes still do not want to be associated with polluting objects and occupations (Desai and Dubey, 2012). This has minimized the number of individuals motivated to manage waste in India. India's government has done very little to motivate or increase the capacity of individuals to enter into jobs associated with waste management (Doron, 2018).

MATERIALS AND METHODS

This study is an iterative, inductive, constructivist qualitative (Charmaz, 2014) case study examining the maintenance process of CWs for DWT that provides agricultural irrigation water. Mental models were indirectly elicited through semi-structured interviews (Jones et al., 2014). The first author relied on the constant comparison process (Charmaz, 2014) between each of the constructed wetlands, communities, and stakeholder groups to understand the dimensionality of the process of maintaining the CWs.

Theory: Mental Models and Plural Valuation

How to best elicit, share, and examine the plural valuation of ecosystem services in community development to limit the effects of power between stakeholders has not been thoroughly explored (Arias-Arévalo et al., 2018; Jacobs et al., 2020) but has been widely seen as problematic (Zafra-Calvo et al., 2020). Mental models may provide a method for eliciting stakeholders' plural valuation of the CWs. It allows multiple perspectives to be collected in a way to develop an understanding of how communication and power are dealt with across gaps and overlaps between stakeholder groups (Friedrichsen et al., 2019).

Mental models are cognitive structures of how the world works. Mental models are built through experiences and cultural norms. Individuals from the same sub-cultural background will hold a collective cultural model of how the world works. Individuals use their mental models to filter incoming information and predict the future outcomes of decisions (D'Andrade, 2005; Quinn, 2005; Jones et al., 2011). Individuals may have multiple partial or whole cultural models depending upon their group memberships (Quinn and Holland, 1987).

Comparing and contrasting stakeholder mental models to identify gaps and overlaps can provide insight into how natural resources are managed and used to facilitate community development (Jones et al., 2014; Friedrichsen et al., 2018, 2019). The study of mental models can be elicited individually or in group settings, depending upon stakeholder preference, power structure, and how stakeholders prefer to express their values.

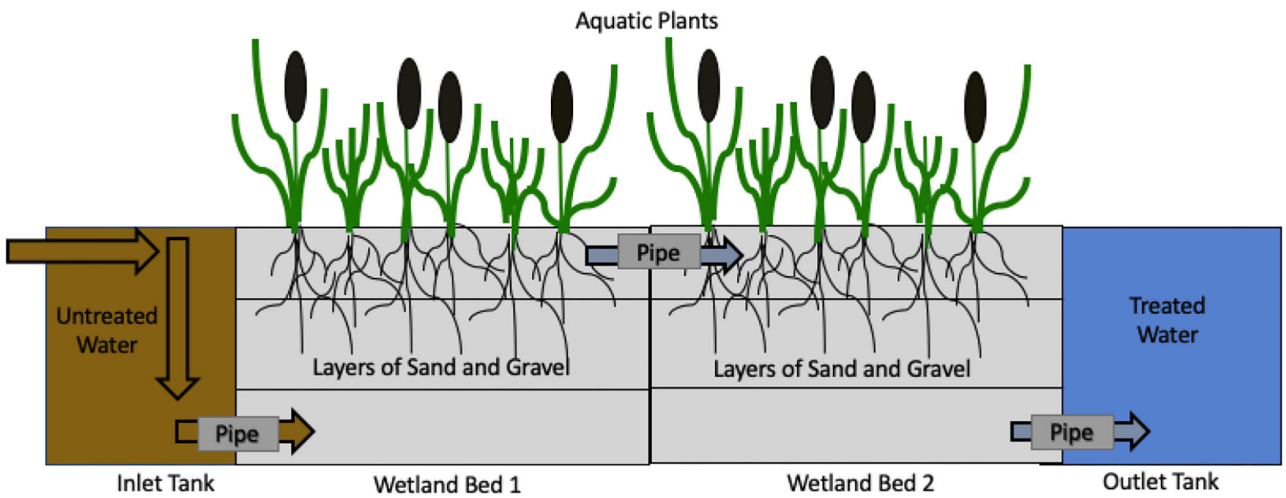

FIGURE 1 | Basic design of horizontal flow CW implemented in the communities.

Study Design and Sampling

This study was designed to examine the maintenance of CWs within established research and extension programs. The International Crop Research Institute for the Semi-Arid Tropics (ICRISAT), as part of their Integrated Farmer Participatory Watershed Management Model (IFPWM), built ∼30 CWs for communities across south India that had limited access to water for crop production and existing concrete drainage systems that collect mostly gray WW. ICRISAT aimed on increasing agricultural irrigation water quality and improving the food safety of crops grown with WW through disseminating CWs (Datta et al., 2016, 2018). The horizontal flow, gravity-based CWs mimic and recreate natural wetlands' ecosystem services by delivering clean water via supporting processes of filtration and sedimentation of particles, uptake of extra nutrients in wastewater, and reducing microbial loads in outflow (**Figure 1**). The CWs were in various degrees of surface and subsurface flow at the time of observation. Of the six CWs observed, two CWs had primary treatment (gravel tanks or sedimentation pond). CWs often lack primary treatment in developing countries (Denny, 1997).

The designed capacity of the CWs ranged from 20 to 56 (m^3/d), serving between 70 and 500 households. The primary maintenance activities recommended by ICRISAT for CWs include harvesting of aquatic vegetation and backwashing every several months. ICRISAT recommended the cleaning of the gravel and sand in the wetland beds approximately every 5 years. Other major, routine, and non-routine maintenance activities were identified by stakeholders, including replacing gravel and sand in wetland beds, mosquito management, and leveling of the wetland bed material to prevent stagnation (Friedrichsen et al., 2020).

IFPWM is based on a participatory development model where a watershed committee is formed that consists of various stakeholders who represent a wide range of religions, gender, and castes. IFPWM is mainly funded by social-responsibility corporations. The watershed committee then chooses what innovations to adopt in the community from a suite of innovations, the innovations' placements, identifies willing farmers, and communicates between the community and ICRISAT. (Wani and Ramakrishna, 2005; Wani, 2008; Wani and Sidhu, 2009; Datta et al., 2018). ICRISAT aims to foster ownership of the CWs by farmers who use the outflow through either monetary contribution to the construction or donated labor. ICRISAT fostered ownership by the community through celebrations centered around the beginning and end of the construction of the CW and handing over responsibility. For the CWs, watershed committee members along with the farmers using the outflow approved the construction, identified the location of the constructed wetland, and oversaw construction and maintenance of the CWs during the IFPWM project duration. Scientists and extension agents provided reactionary advice to the CW's functionality during the IFPWM project duration and collected water samples to monitor water quality. The IFPWM project durations varied per community, depending upon funding available with a minimum of 4 years.

This cross-sectional design compares the mental models of scientists, farmers, privileged, and socially disadvantaged community members, allowing for the examination of how plural valuation of ecosystem services of CWs impacts the dissemination, adoption, and maintenances in the community. Six CWs in four communities were selected to be part of this research study. Selection criteria for their inclusion included: (1) proximity to ICRISAT to ensure that there was communication and knowledge exchange between ICRISAT researchers and the participants, (2) CWs were past their adoption phase by the community and within their maintenance period, and (3) outflow water of the CW was being used for agricultural crop production. The study aimed to include constructed wetlands that were constructed 6 months to 5 years prior and were at the time in a

TABLE 1 | Participants by stakeholder group.

Participant	Number
Farmers using WW	9
Farmer using harvested biomass from CW	1
Watershed Committee members	6
Community WASH maintenance representative	4
Extension Agents	11
Sarpanch (Village president)	3
Scientists	5
Neighbors living near CW (Focus group of 3–6 individuals)	4

period of needing maintenance. Data saturation was determined when no new concepts arose from interviews with two additional extension agents in a seventh constructed wetland in a fifth community (Bernard, 2011). Each community was visited at least twice with at least a month between the initial and final visits. The first author was a research fellow within the CW project at ICRISAT and had prolonged engagement (4 months) with the scientists and extension agents during the entire data collection period.

Sampling purposefully selected individuals who represented all of the various dimensions of maintaining the CWs (**Table 1**) (Bernard, 2011). Interview participants ($n = 39$) were identified and approached by their local extension agents to initiate the conversation with a trusted individual (Warren and Tracy, 2015). Focus groups were conducted with neighbors living near the constructed wetlands ($n = 4$), with each focus group having 3–6 participants. The categories of participants used for the sampling frame in **Table 1** were then grouped into how they perceived the CW valuation: Scientist, Farmers, Privileged, and Socially Disadvantaged community members (**Table 2**). Extension agents had mental models that included segments of various other stakeholder groups' mental models. In general, watershed committee members and the *Sarpunch*es (village president) had values aligned with the category of privileged community members. In contrast, neighbors and community WASH representatives held values that aligned with socially disadvantaged community members. The research was reviewed and approved by the University of Florida Institutional Review Board. The participants provided their oral informed consent to participate in this study.

Data Collection

Data were collected through semi-structured interviews (Laukkanen and Wang, 2015), observations, and tours of the CWs and surrounding communities (Abel et al., 1998). The first author conducted all interviews ($n = 43$) in the spring of 2018 as a research scholar at ICRISAT. All participants gave informed consent. The interviews were conducted in the participants' offices, houses, on roads next to the CWs, or in nearby community areas to improve reliability and validity of their responses (Jones et al., 2014). The interview guide was developed and pilot-tested with extension agents (Zahnd and Willis, 2007). The interview guide was developed during data collection as preliminary data analysis occurred throughout the data collection process to include emerging themes (Charmaz, 2014). The objective of the interviews was to elicit the stakeholders' mental models of the maintenance of the CWs. Interview topics included the CW planning process, perceptions of water quality of effluent, CW functionality and maintenance, responsibility for CW maintenance, implementation process, barriers to implementation, design suggestions, explanations of design modifications over time, and challenges and benefits of the CW. Most participants were eager to participate in the research, especially the farmers and watershed committee members. They gave tours of the CWs and the farmland where the irrigation water was used. Local politicians and some scientists were less eager to participate, although they did consent and find time to contribute. Socially disadvantaged community members were meager but appreciated the opportunity to share their perspectives. Interviews lasted from 15 min to 2 h. Interviews with CW neighbors were shorter and interviews with scientists, extension agents, and farmers using the wastewater were longer. Interviews with scientists and extension agents were conducted in English. Interviews with other participants were conducted in their first language, either Kannada or Telugu, using three translators. A subsample of the Telugu interviews was spot translated by the second translator to ensure accuracy. Field notes were taken after community visits.

All interviews were audio-recorded and then transcribed by the first author. Participants were asked to draw the constructed wetland during the interview, which added to understanding their perceptions of the unit (Literat, 2013). Interviews lasted from 15 min up to 2 h, depending on the individual's level of interaction with the CW.

Data Analysis

A constant comparative method was used for data analysis (Glaser and Strauss, 1967). The first author, who used peer debriefing during the initial data analysis, coded all the interviews in NVivo (version 12). There were 166 emergent themes, grouped into 15 categories (Bernard and Ryan, 2010). **Table 3** presents the codebook with all categories, and **Table 4** gives an example of emergent themes from one code category with representative quotes. The 3CM card sorting technique (Kearney, 2015), coupled with debriefing conservations, was used with three participants to provide feedback on the findings of the emerging categories during data collection and analysis as a form of member checking (Birt et al., 2016). Memos were written during data collection, analysis, and diagramming (Charmaz, 2014) to understand the differences between varying CWs and communities (Glaser and Strauss, 1967). Mental models were created and represented with influence diagrams for each stakeholder group (Jones et al., 2014; Friedrichsen et al., 2018). A process model (Morgan, 2018) was created to explain the maintenance of the constructed wetlands. It was developed through iterative diagramming during the data collection, data analysis, and peer debriefing (Charmaz, 2014). Peer debriefing was used throughout the data analysis process (Saldana, 2015). The model builds upon the work in Friedrichsen et al. (2020) of the importance of ecological knowledge on monitoring the CW

TABLE 2 | Stakeholder groups, cultural models and mental models of CW maintenance.

Cultural mental model	Stakeholders with part or whole mental model alignment	Mental model
Expert	Scientists, Extension agents	Instrumental ecosystem service value of CW greater than cost of maintenance
Beneficiary	Farmers using WW, farmer using harvested biomass from CW, Extension agents	CW has agricultural value with or without maintenance
Socially disadvantaged community member	Community WASH maintenance representative, neighbors living near CW, Extension agents,	Yuck devaluation is greater than the value of maintenance
Privileged community member	Watershed committee members, *Sarpanch,* Extension agents	Yuck! CW maintenance is not my responsibility

TABLE 3 | Code book for data analysis.

Categories
Suggestions for design
Responsibility for CW maintenance
Challenges caused by the CW and barriers to maintenance
Knowledge of CW maintenance
Perceived benefits of CW
Monitoring of CW
Mechanization of CW maintenance
Composting of aquatic vegetation biomass
Indicators of CW functionality
CW labor and maintenance
Gender and CW
Farmer characteristics as related to CW outflow use
Location of CW
Payment for CW maintenance and CW income generation
Maintenance activities

performance within stakeholder communication and perceived utility of maintenance for water quality.

RESULTS

The development of the maintenance process of the CWs within the communities followed a linear process that led to the current state of plural valuation, governance, and maintenance (**Figure 2**). The results are divided into three sections that address each of the research questions. The first section compares and contrasts the mental models of experts, beneficiaries, privileged, and socially disadvantaged community members related to the plural valuation of ecosystems of CWs. The second section examines how the yuck factor impacted CW maintenance related to being a leverage point for social division and decreasing the dignity of the maintainers. The third section gives suggestions to improve the human-centered design of the CW to overcome the plural valuation of the ecosystem services perceived by stakeholders to address the yuck factor. Minimizing the yuck factor promotes maintenance and increases the perceived benefit for maintenance and, consequently, motivates maintenance.

TABLE 4 | Codebook example of themes grouped under the category of CW labor and maintenance.

Theme	Representative quote
Village servants do the maintenance	Interviewer: Whose responsibility is it to clean out those drains? Farmer 32: Gran panchyt. There is a person called village servant who is appointed by the *sarpunch* who needs to take care of it. Interviewer: Why is he not taking care of this? Farmer 32: [The location of work is] Alternating, the village servant will change the location of cleaning so by the time he cleans this location it blocks there
Pay more to clean out	Maintenance 11: More money because this is dirty, difficult work
Labor comes from another village	Maintenance 49: We are from a different village, we came here only for today.
No labor	Extension 37: Responsibility, sincerely they (the community) have to do the harvesting. Some villages you will not get the labor. They, the *panchyt* or farmers, have to bring the labor from outside. So it will be cost more.
Caste and labor	Extension 46: There is a probable with it being viewed as dirty work. And there are cultural taboos associated with dirty work.
Protective gear	Scientist 26: There is a fear to go inside and to do the cleaning. That is why we suggest people who are cleaning the wetland that they should have protective gear. In the watershed we have given the protective gear also. But to implement it properly is difficult. I have personally seen some people who enjoy playing with snakes even if you give them the protective gear they will say I don't need. So it is kind of, snakes prevents a lot of workers to come for the work. Then also we are required to give them googles, gum shoes when they are going inside.

Plural Valuation of Ecosystem Services

The mental models of CW ecosystem services held by experts, beneficiaries, privileged, and socially disadvantaged community members were strikingly different (**Figure 3**). Scientists perceived

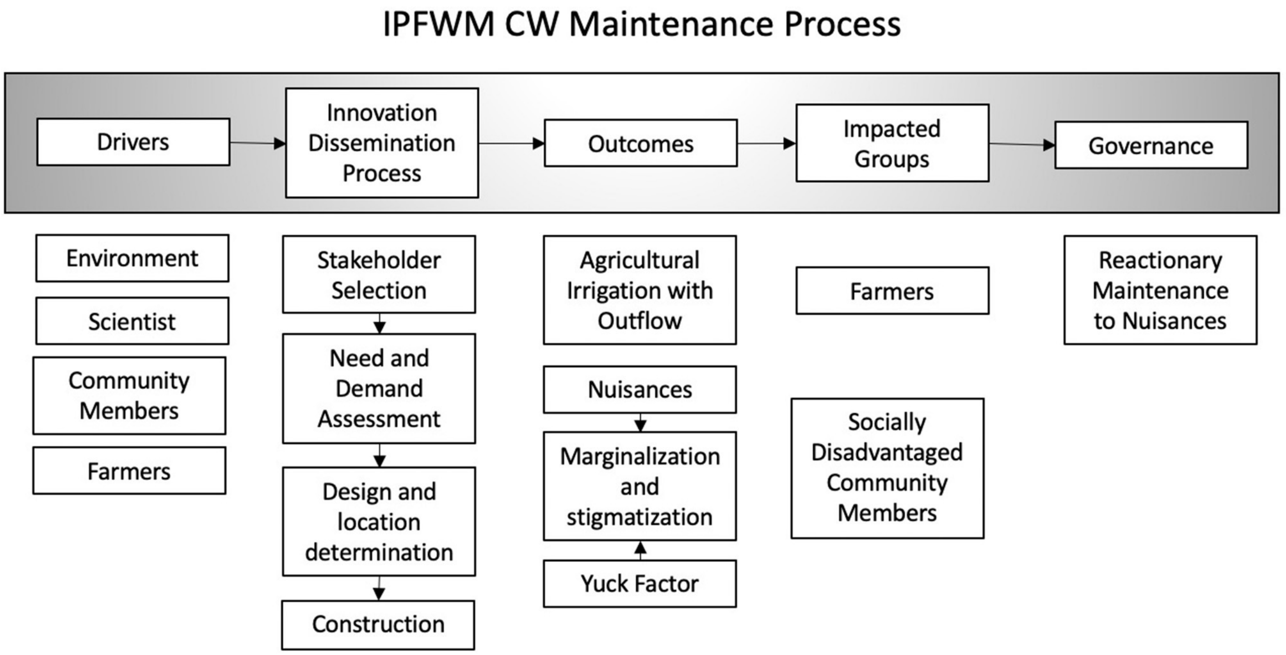

FIGURE 2 | IPFWM CW implementation and maintenance process.

the CWs provided a valuable ecosystem service of treating WW in the community while providing irrigation water for nearby crops. Of non-scientists, only beneficiaries perceived a direct benefit of the CW's ecosystem services, which was the value of improving their occupational health. The community did not perceive the CW provided any ecosystem services to them. They only saw the CW as providing an ecosystem service to the farmer and socially disadvantaged community. Perceived misconceptions by the community related to WW reuse and food safety may have limited perceived value and ecosystem services, influencing their motivation to contribute to maintaining the CW.

Plural Valuation of CW Maintenance Among Stakeholders

Stakeholders had contrasting and divergent mental models of ecosystem services provided by the CW. Privileged community members and socially disadvantaged community members did not perceive any ecosystem services (**Figure 3**). Experts perceived that the CW would be maintained by the community because of the multiple ecosystem services the CW provided the beneficiaries, privileged, and socially disadvantaged community. Scientist 51 said, "They are facing water scarcity. If we build a wastewater treatment it means it will be helpful to them… We can help the farmer, villagers, to give the technology [and] to give the technological support but maintenance they have to take care." Experts perceived the communities would perceive value from the multiple ecosystem services provided by the CWs.

However, there was little perceived ecosystem service value by the community to maintain the CWs for the sake of improving public health. No privileged nor any socially disadvantaged community members mentioned a public health benefit from the CWs or maintaining the CWs. Instead, sanitary worker 12 said, "Farmers are ready to pay [for the maintenance]. They are getting a benefit; they are getting water." When asked what would happen after ICRISAT officially ended their IPFWM and left the CW maintenance to the communities, extension agent 46 said, "This project will end because no one will spend the money to maintain it." The extension agent went on to explain that only once the community understood and valued the benefit of the CW to improving their environmental and health conditions would they spend money to maintain the CW.

Most farmers using the CW outflow had used WW previously, so they did not perceive changes in their water supply. However, several noted that the CW infrastructure (drains and outflow holding tank) did improve their ability to collect WW for irrigation. Several farmers did perceive health benefits:

> *I am not getting any types of health problems. That time [before the constructed wetland], I also have some health problems. Allergies. That time. This time [with the constructed wetland], I am not getting any type of health problem—allergies. (Farmer 4)*

In addition to saying the water quality had improved since CW installation, Farmer 4 also asked that the CW be expanded to improve the quality of the outflow. Farmer 5 noted reduced skin allergies from using the outflow of the CW in addition to improved crop yields. Farmer 5 said, "[Now,] I am getting good water, good yields, good crops. No problem for this crop. Before, [when] I was using the [untreated] wastewater. The crop was somewhat affected." Also, several farmers said that wastewater is better than groundwater because it provides nutrients to the crop.

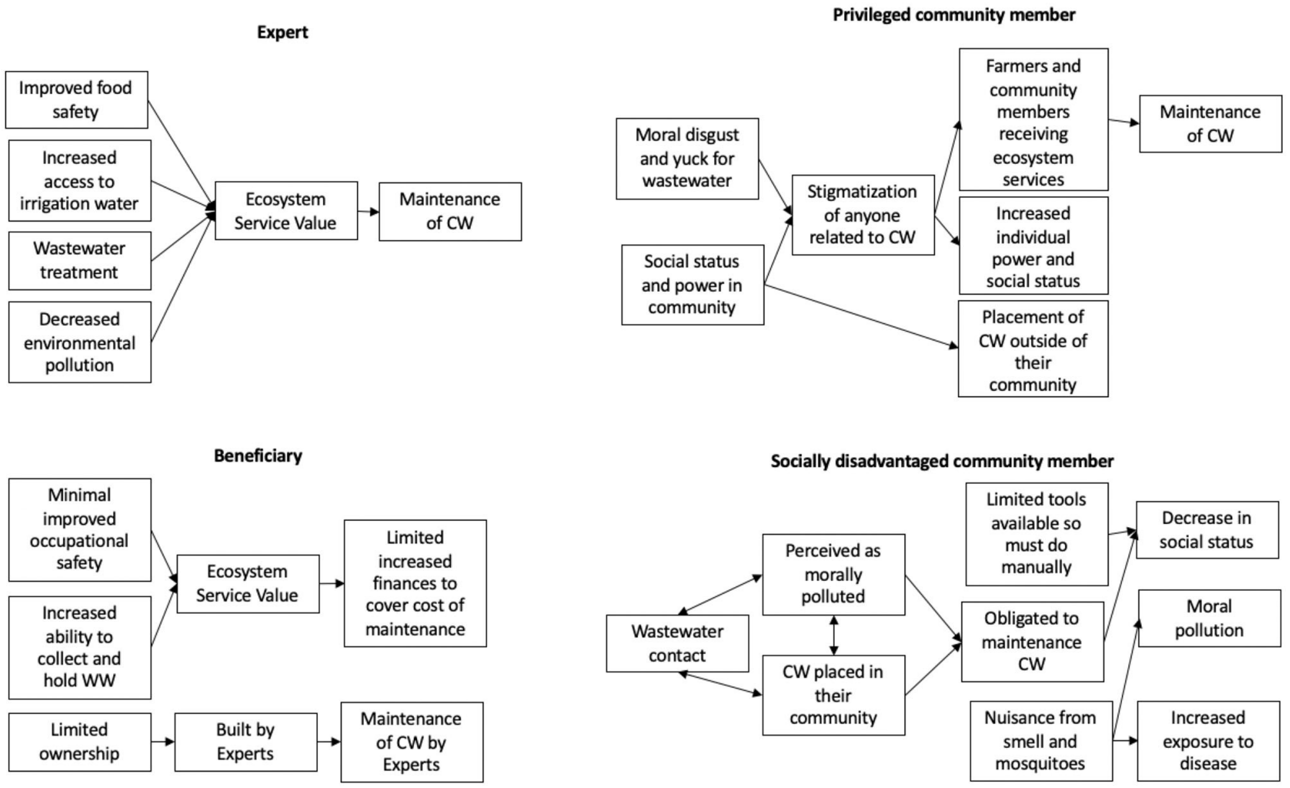

FIGURE 3 | Mental models of plural valuation of ecosystem services by stakeholders.

Food Safety

There was a limited perception of an improved food safety benefit by the privileged and socially disadvantaged community, or farmers. Several misconceptions and hesitations impacted the use of the outflow of the CW, likely further increased social stigmatization of the CW, limiting the perceived food safety benefit. When probed about the safety of using WW for crop production, Farmer 18 replied:

> *They are growing and eating spinach, eggplant, leafy vegetables. There is no effect [on our health]. [However, vegetables are grown] inside [the soil], potato, carrot, these types of crops no need to grow using treated wastewater… When the root vegetable is growing inside in the ground. The wastewater is going inside, and the vegetable will absorb any chemicals. Leafy vegetables are grown above the ground [and will not be exposed to the wastewater]. (Farmer 18)*

This belief was also echoed by Farmer 31, who was using the outflow from a CW to grow only above-ground vegetables (eggplants and tomatoes) instead of below ground vegetables (onions). The various levels of understanding and misconceptions related to public health and WW in agricultural irrigation are also noted by scientists working on the project.

> *Food contamination is very important. Actually, farmers or villagers are not that aware of food contamination, so this is an aspect that is important from the policy side. What I see is local people irrigating salad crops directly with raw wastewater. I don't think they really understand the relation with wastewater and their health and well-being. I don't think that awareness is there. (Scientist 26)*

The misconceptions and lack of knowledge of food safety related to WW for fresh vegetable production may perpetuate negative opinions within the community related to reusing WW. This may have impacted both acceptance and perceived benefit of maintaining the CWs for improving public health. The lack of an assigned value of the ecosystem services provided by the CW resulted in both the privileged and socially disadvantaged community members and farmers performing limited maintenance on the CWs.

Since the communities do not perceive or value the experts' expected ecosystem services from the CW, the privileged and socially disadvantaged community members are not willing to place a monetary value on its maintenance.

> *What I feel the end user [the consumer], I don't think he will worry very much about the maintenance of the wetland. That is what I feel. If there is a farmer who has the experience, like directly seeing a difference, like how his skin is being impacted, he will definitely fight for the wetland, for the maintenance. (Extension Agent 25)*

Farmers, privileged, and socially disadvantaged community members did not perceive value from the treated WW. They, therefore, were unwilling to spend time or money on the maintenance of the CW.

Cultural Beliefs: Morality and Yuck

This section explores the moral dimensions of the plural devaluation of the ecosystem services through the yuck factor. More specifically, the perceived devaluation of the ecosystem services provided by the CW and WW treatment contributes to social division and discrimination within the community. Experts perceived a value in the ecosystem services provided by the CW, however, the community saw the CW as morally degrading. The contrasting mental models of ecosystem services valuation and their relationship to the CW maintenance led to limited maintenance by stakeholders. Instead, it fostered social tension, stigmatization, and marginalization (**Figure 3**).

Location

ICRISAT devotes a considerable effort to identifying and working with a diverse group of individuals on the watershed committee board that represent multiple genders, castes, and religions. These watershed committee boards are charged with participatory planning and selecting the location of the constructed wetland.

> *The upper castes don't want to strongly relate themselves to wastewater. That you might have seen. So a lot of the time, locations of the wetlands are all towards a certain area, which is in proximity to the lower caste community… The location is always closest to the least favored community. (Scientist 25)*

However, the participatory planning escalated social inequality within the community, exposing the socially disadvantaged community members to moral pollution and violating their purity by locating the CWs within their neighborhoods.

Due to the topography, WW flow may influence where one community (with greater or lesser social hierarchy) lives in the village. This can lead to individuals perceiving an unequal distribution of the polluting nature and nuisances of the CW.

> *The plants in the constructed wetland are dropping their leaves right now and blocking the constructed wetland… Because of the dropping leaves, there are mosquitos, children are falling sick, and the odor is like hell in the night times. Whenever we tell the sarpanch [village president], field officers, watershed committee they are not taking care of it…they said that we need to clean it on our own. How can we do it? It is complete village. (Socially Disadvantaged community member, CW Neighbor 15)*

The local officials are privatizing the CW nuisances, placing the responsibility to maintain the CWs on the socially disadvantaged neighbors. The local officials do not see maintenance as a larger community public health effort and the CW as a public resource. At the time of data collection, the CW next to neighbor 15 had been modified to reduce the nuisances that the lack of maintenance had caused—the cement drainage system in front of the inlet tanks was broken and the inflow was being directed around the CW and across neighboring fields.

> *The water got blocked there. We diverted the canal. There is a jam. There is a small stone, we took out the small stone, so now it goes out the other canal and not going into the constructed wetland. We did not do that. The municipal person that came, we told him the problem, we just complained about the problems, mosquitos, pigs, garbage, he diverted that canal.… Whenever people like you come, they come and look at the conditions, they talk about the constructed wetland, other than that no one is going to talk about the constructed wetland except you guys. The maintenance is not good. …We told 3-4 times, we told the committee members, but they did not respond. (Socially Disadvantaged community member, CW Neighbor 15)*

Socially disadvantaged community members may lack the necessary social capital, power, or empowerment to provide feedback essential for timely and effective maintenance. Without effective maintenance, the CW becomes a devaluing ecosystem service and is a source of moral impurity, which negatively compounds socially disadvantaged community members' social standings and mitigates the value that the CW brings to the community. The net result is a degeneration of social cohesion in the community.

Social Division

When promoting a CW's maintenance, the yuck factor can exacerbate divisions within the community, bringing out prejudices between the individuals with power and socially disadvantaged community members. One stakeholder perceived difficulty in communicating with the community to stop putting garbage inside of the CW. Watershed committee member 18 said, "They are not learning. They did not hear. So once again they put inside… The community people are *Dalit*, low caste, so they are not understanding those words. They are aggressive people like that." The prejudice by the watershed committee member responsible for maintaining the CW and securing resources from ICRISAT has limited the community's ability to act cohesively and tackle the CW's poor maintenance issue.

Dignity and Labor

Finding labor to maintain the CWs was difficult. It often required hiring daily labor from other villages, costing 1.5-2 times the local daily wage, because there was no perceived value in the CWs. A community sanitary manager 11 said, "I am doing technical work, not hard work. I'm not doing the work. I am advising laborers. Not doing the work. Members are there [from] *panchayt* [local village administrative units] office, 20 members. These people only doing this work, otherwise they will get from outside laborers." The community sanitary manager 11 is not a socially disadvantaged community member, consequently, he did not work inside the CW. Instead, he contracted individuals to do manual labor of maintaining the CW, which is considered polluting.

In some of the communities, it was perceived that only socially disadvantaged community members could do the maintenance since the CW was associated with WW. Scientist 52 explains,

> *Cleaning and other things certain caste people might not like to get their hands dirt. But when there is some economic benefit coming out of it. The farmer who is enjoying the benefit might put his own money to get that cleared—if he really wants. He might hire people and get it cleared, [and] get it maintained because it needs certain cleaning periodically. (Scientist 52)*

Even when the CW work could be mechanized, communities preferred to hire socially disadvantaged community members to do maintenance. Watershed Committee Member 18 said, "Actually, weed whacker is difficult. Manual work is good... Need to do work with manpower only. Laborers also getting some work. They are getting some job, some money; the work is only doing *Dalit*s." In contrast, one farmer requested a weed whacker during the interview, and one extension agent mentioned their utility when labor is unavailable. Maintenance of the CW degrades individuals' purity by doing the maintenance and contributes to poor social cohesion in the community. Thus, only individuals who are already perceived by the community as having degraded sanctity will do the manual work within the CWs, and they will then seek machinery to avoid physical contact with the WW.

Compounding Social Stigma

Without proper tools to do the CW maintenance, there is increased social stigma associated with maintaining the CWs. Instead of appearing as a dignified job, maintenance becomes associated with manual scavenging. Jumping into the WW inflow, Farmer 42 removed sludge and garbage with his hands while standing mid-thigh deep in the untreated WW. Farmer 42 had no tools or safety protection to do this work. In addition, another farmer and one maintenance individual requested protective safety clothing from ICRISAT to maintain the CW during the first author's visits to the CWs. Not having the correct tools to maintain the CW reinforces the perception of categorizing the maintenance of the CW with manual scavenging.

The cost of maintenance of the CW caused further burden social stigma to the socially disadvantaged farmers using the WW outflow. The farmers who accepted the CWs frequently had already been using untreated WW. In attempt to improve their social status and purity, they accepted the adoption of the CW. However, these already impoverished farmers unexpectantly became saddled with the burden of maintenance because the community perceived they were receiving the benefit. The focus group of neighbors in community 23 responded to the question of who should pay for the maintenance by saying, "Farmers of [village] only. Why? Because they are getting benefit from it. The reason they have to maintain these wastewater treatment plants." The limited profit the farmers were receiving from irrigating an acre or two would be considerably less than the cost of maintenance. The yuck factor of WW leads to the degradation of the sanctity and dignity of the individual maintaining the CW. The maintainers' dignity is further compromised by their lack of available appropriate tools and the financial burden of maintenance. Without proper maintenance, tools, and available capital for maintaining the CWs, then the CW nuisances are compounded. For example, in extreme weather events and flash flooding, "If rain comes, water stagnation will be here. And usually because of the stagnation of this water bad smell mosquitos, malaria and typhoid," said Participant 43.

However, with the installation of the CW, one farmer perceived an increase in the social acceptability of his practice of using WW, leading to an increase in social standing and dignity within the community. This was because the farmer gained attention from the national level news and foreign visitors to his farm. That attention improved the farmer's social status.

The yuck factor impacts the location of the CWs, the communication feedback loops about the necessary maintenance, and who will do the maintenance work in the CW (**Figure 3**). The yuck factor is currently augmented by the limited availability of tools and inadequate financial capacity for the maintenance work. All of which further degrades the maintainers' dignity. The CW maintenance work is perceived to be so yucky or polluting that individuals who are already spiritually impure are the only ones that can do the work, which decreases social cohesion in the communities. Without proper maintenance, the nuisances foster a perceived severe public health situation.

Human-Centered Design to Promote Maintenance

The participants were excited to share suggestions for improving the CWs. Many of the suggestions provide important insight into how to design and disseminate the CWs for overcoming the yuck factor and giving value to the maintenance of CWs to promote ecosystem services. Improving the functionality of CWs and preventing the cascading nuisances that create negative social stigma in the community are essential design considerations for accommodating the stark differences in the plural valuation of the CWs' ecosystem services.

Design of the CW

Participants stated that an appropriate design would shift the maintenance work from manual to mechanized. Manual work with human feces, "manual scavenging" is illegal in India and is considered spiritually polluting (Permutt, 2011). The participants perceived that the maintenance of a CW was, to a degree, "manual scavenging." Designing CWs so that the maintenance work can be done with machines will enable maintenance work to be less degrading and spiritually polluting. For example, creating a design that allows for the use of "*honey suckers*," tankers designed to empty septic tanks, to remove the built-up sludge would eliminate the need for manual work inside the inflow tanks of CWs. Farmer 13 said "Cleaning you are asking? Manpower is not workings inside, machinery is better, easier to work."

The participants had many additional suggestions for improving the CW's design for overcoming the yuck factor. Their suggestions included: improving the adaptability to the local context, aesthetics, ease of maintenance, and reducing clogging (**Table 5**).

An advantage of DWT in India is that it can be designed to accommodate local conditions associated with purity and

TABLE 5 | Design suggestions for improving the maintenance and acceptability of the CW within the community.

Adaptability to Local Context
- Constructed out of flexible and easily modifiable structure materials (not concrete)
- Installation of a primary treatment system before CW
- Outflow management (allow groundwater infiltration from outlet tank vs increase storage capacity of outlet tank)

Aesthetics
- Build solid fence around so community cannot see, and animals cannot fall in
- Use plants in CW that repel snakes and mosquitos
- Park like atmosphere for public use
- Covered inlet and outlet tanks to reduce nuisances
- Move CW away from village
- Move CW away from village's drinking water source
- Functioning subsurface flow design
- Increase velocity of water moving through CW

Ease of Maintenance
- Walkways in unit, so it is easier to remove plant biomass without falling into filtration tanks
- Physical barriers to prevent garbage from entering (mesh and fences)
- Designed so honey sucker can remove sludge
- Designed so all maintenance activities are mechanized
- Better designed so that outflow can effectively remove clogging
- Improved designed so plant biomass can be removed from structure easier

Improved Functionality
- Install a settling tank before CW
- Designed to better handle storm water and all the silt and garbage that comes with it
- Fence or mesh to prevent garbage from entering CW
- Remove internal walls within CW so that there is one single gravel filtration tank
- Larger gravel to reduce clogging

social stigma. However, local and climate constraints are not known until the CW is installed and begins to function. Even if communities are involved with the CW's design and placement, they may have varying valuations of the CW, and often have no realistic understanding of the system. The community members are not prepared for the social stigmas that might arise or barriers to efficient maintenance. They do not have an existing mental model that could help them understand what the CW does or its maintenance requirements. A CW design needs to be easily modifiable with little expense to the community as they learn about its functionality, social implications, and maintenance needs to ensure successful long-term implementation. The design of CWs need to account for and limit maintenance situations that contribute to social stigmatization and instead provide opportunities for social advancement through maintenance. These design parameters may help improve the perceived value of CWs' ecosystem.

The aesthetics of a CW is essential for building an additional ecosystem service for the community to value while preventing social stigmatization. Scientist 52 said, "This water should be used and then create a green patch out of know where, someone sees a green patch it becomes really spectacular people will come and look at it. [And the community will ask] When everything else is gray, how is this green?" Scientists often complained that the participants were spreading rumors that the CWs were breeding locations for mosquitoes. Designing CWs to promote positive attitudes and values toward their aesthetics may prevent rejection of the CWs by the greater communities after installation. Suggestions include developing a park or planting flowers within or nearby the CW.

Reducing Maintenance Frequency

Watershed committee member 33 suggested creating a second set of "four tubs" or siltation tanks to serve as a second inlet. The community could divert the inflow into the second set of tanks when the first four siltation tanks are clogged with sludge. This would improve the functionality of the CW and ease maintenance. "When the sludge is silted in that particular place... We have suggested, one more four tubs besides that. First three months this one, second three months this one." This would allow the community time to clean or replace the gravel in the siltation tanks every three months, diverting the water to another set of siltation tanks instead of around the CW. This would improve functionality and prevent public nuisances of the CW associated with the clogged inlet tanks, such as smell, stagnant water, and mosquitos.

Associated Community Infrastructure

Without proper community infrastructure and public programs, the CW becomes the defacto stigmatized infrastructure dealing with everything impure (garbage, feces, and use of the site as an open defecation location), increasing the community's perception of purity. Accompanying the dissemination of the CWs with solid waste management and open defecation awareness programs helped prevent the cascading impacts of insufficient WASH infrastructure. In two communities, ICRSAT and the local government worked together to find land and establish a solid waste collection service to diminish the amount of solid waste that would flow into the CW from stormwater and individuals disposing of garbage.

The CWs are stigmatized as being polluting in nature due to their association with open defecation. In one community, the *sarpanch*, the *panchayat* president, discussed the extensive and effective anti-open defecation behavior modification program she had created to change her community members' behavior to improve public health. She emphasized her program of finding individuals and posting murals across the community to change the social norm of the acceptability of open defecation. Reduction of open defecation decreased CW's use as an open defecation site.

The yuck factor associated with CWs may be diminished and the perception of instrumental ecosystem valuation improved with the human-centered design of the CWs. Additionally, the establishment of an associated WASH community infrastructure and programs to limit open defecation and promote solid waste management will improve the inflow to CWs and associated perceptions.

DISCUSSION

In this case study, we examined the yuck factor's moral dimensions as related to WW and strategies for overcoming the yuck factor to promote the maintenance of decentralized WW treatment. The foundational moral value of purity or sanctity was not appropriately and effectively included in the planning, design, implementation, adoption, or maintenance of CW. We showed that the yuck factor might become a leverage point for social division and inequality in the community if there is not strong enough social cohesion. ICRISAT has done a considerable amount of work to identify ways to address these variables, however, without also addressing plural valuation of WW, yuck factor, social cohesion, social stigma, and perceived benefit of untreated WW, it may be difficult to move forward. This case study provides an essential comparative piece for examining plural valuations of ecosystem services of a constructed environment and the role of the value of sanctity, as well as its relationship to adoption, maintenance, and long-term implementation of an innovation. Based on this case study, we propose a preliminary innovation process model that integrates a plural valuation framework (PVF) and human-centered design to facilitate CW maintenance by communities. This proposed model overcomes the challenges of contrasting plural valuation, yuck, and power differentials within communities and may facilitate long-term maintenance of CWs (**Figure 4**).

Plural Valuation Framework

In reference to community water management, Schouten and Moriarty (2003) stated, "At its worst, community management is nothing more than the dumping of what used to be government's responsibility on to the community." The management and maintenance of decentralized WW treatment technologies is a dynamic and difficult behavior for ensuring voluntary continuity within communities. Other variables identified in DWT literature include accountability, willingness to pay, ability to pay, enforcement of rules, sense of community ownership, social cohesion, the existence of appropriate governance rules and regulations, and leadership. They all contribute to reinforcing or undermining social cohesion (Schouten and Moriarty, 2003; Saravanan et al., 2009). Inappropriately assuming that communities have created an equitable cooperative agreement during participatory planning and adoption may be at the core of why community-based watershed management has not succeeded (Saravanan et al., 2009; Starkl et al., 2013b).

PVF, a natural resource management planning process developed around the concept of plural valuation, recognizes power dynamics impacts certain cultural groups' values of nature, intentionally or unintentionally, excluded from ecosystem service valuation (Arias-Arévalo et al., 2017). Therefore, using PVF as a template for a CW implementation's planning and innovation process may prove beneficial to addressing these variables. People tend to value and prefer opportunities to demonstrate competence (Deci and Ryan, 2012), protect community status, and environmental quality (Haidt, 2007). How they choose to do this, however, is a function of culture and opportunity. The PVF focuses on providing an equitable space for social learning to solve these challenges. The first step is eliciting the plural valuation of the CW (e.g., mental models) and understanding the community's cultural landscape in a manner that is comfortable to all community members. Then, PVF suggests managing power dynamics through creating a third place, a place removed of pre-existing historical power dynamic struggles, that is comfortable for everyone, providing a place of social learning through the implementation process of the CW (Jacobs et al., 2020).

Human-Centered Design of CW

To facilitate long-term adoption and maintenance, the CW design must be perceived to be appropriate for and straightforward to the community members. To accomplish this, CWs need to be redesigned (Denny, 1997; Laugesen et al., 2010a; Møller et al., 2012). Human-centered design is an iterative, participatory design process that focuses on emphasizing and understanding the users' experience, needs, and cultural context, and then refining the design based on a formative evaluation. Human-centered design relies on a participatory methodology to understand the community's needs, including the cultural meaning they create from interacting with the CW (Giacomin, 2014).

This case study suggests that CWs could be made more appropriate if their designs would limit human contact with WW, consequently facilitating and enhancing dignity, even improving social cohesion within the community. To minimize human contact with WW, CWs need to be designed with human-centered design standards that focus on the how the CW is maintained, its ergonomics, and its yuck factor, while being considerate of the users' meaning of the maintenance. Additionally, the CW should be designed to adapt with accompanying capable governance systems responsible for maintenance, including modifying the system based upon feedback from the community.

Proposing a human-centered design approach is a paradigm change in the innovation process of how CWs are designed from a science-based, reductionistic approach to designing a system for achieving specified environmental quality thresholds that include the cultural contexts of the use and meaning of the CWs (Gauss, 2008; Laugesen et al., 2010a).

CW implementation planning should incorporate every stage of the WW system from collecting wastewater, treating wastewater, managing and creating valued outputs (e.g., treated WW and composted sludge), providing energy or renewable energy for the system, integrating the CW with the local situation making a park or providing wildlife habitat as appropriate to needs of community, creating an institutional structure that supports management and finances for supporting maintenance (Laugesen et al., 2010a), and implementation with the associated missing WASH infrastructure (e.g. solid waste management) (Gauss, 2008).

We would like to acknowledge that this process model was developed from only one case study and that once the plural valuation of ecosystem services, yuck factor and social cohesion, and human-centered design are addressed by technology transferring institutions, new variables may arise that impact maintenance.

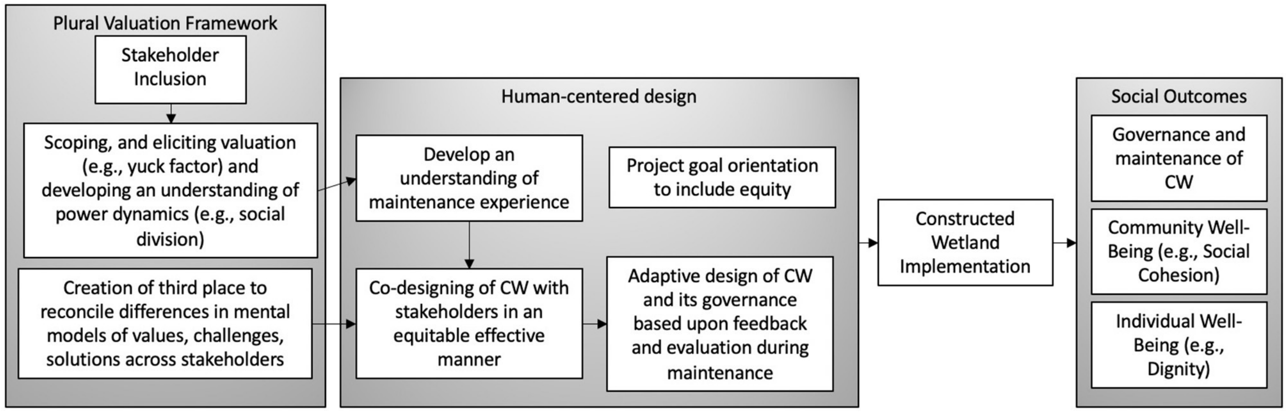

FIGURE 4 | Plural valuation and human-centered design for CW innovation.

Limitations

Because there was limited maintenance by the community at the time of data collection, this case study does not include a thorough understanding of governance and agency within the community as related to maintenance of the CW.

The author is a white female from the United States, who was a research scholar at ICRISAT during data collection. ICRISAT provided the translators and drivers. The participants may have perceived the author as a member of ICRISAT. Individuals who were interviewed may have altered their responses depending on their alignment with ICRISAT and IFPWM. To mitigate this limitation, the sample of individuals came from street intercepted neighbors living next to the CWs. The sample of participants was not limited by ICRISAT's contacts. Scientists were not present nor involved during participant identification or data collection. Data collection and participant selection only occurred with the translator. During data collection, ICRISAT was writing grant proposals to renew Water4Crops.

The case study within this research is only one example, and the explanations cannot be generalized to other DWT units' maintenance. We would like to encourage future research into the maintenance of DWT units, so a general theory could be developed over time and improve DWT outreach globally.

Recommendations

Key insights from the literature on the dissemination of the CWs and to facilitate participatory development and long-term maintenance include:

1. Human-centered design is adaptable, modifiable, and durable, facilitating adoption and maintenance in the face of change with limited non-routine maintenance requirements (Laugesen et al., 2010b). The design must support maintenance that does not cause anyone to compromise their physical or social-religious concerns about purity.
2. Low-cost design and maintenance of CWs (Laugesen et al., 2010b). Access to tools and finances to appropriately and effectively maintain the CW without social stigma or financial burden.
3. Dissemination and participatory planning which does not aggravate existing or create new social divisions within the community (Arias-Arévalo et al., 2018; Jacobs et al., 2020; Zafra-Calvo et al., 2020).
4. Appropriate institutions to support regulation, fundraising for maintenance, generate public support for the project and take responsibility for maintenance (Brix et al., 2011; Møller et al., 2012; Starkl et al., 2013b). For example, technical assistance for communities could be provided at a clustering of DWT scale (Gauss, 2008; Starkl et al., 2013a).
5. Long-term maintenance planning with local community commitment and buy-in (Laugesen et al., 2010b; Rashid and Pandit, 2019).

CONCLUSIONS

Constructed wetlands in rural India have the potential to provide important ecosystem services of DWT. Currently, most of the WW in India from 1.3 billion people goes untreated and is released into the environment or reused without treatment in agricultural irrigation (National Sample Survey Office, Ministry of Statistics and Programme Implementation, 2016). DWT provided by CWs offers the potential to reduce disease and environmental degradation in rural communities. However, widespread adoption and maintenance of DWT units has not occurred despite technological innovation and capital investment. This case study provides a preliminary understanding of how plural valuation of ecosystem services, yuck, and moral disgust impact maintenance of DWT units. This case study is critical because few other community-based examples of plural valuation of ecosystem services related to WW treatment have been explored. This research is intended to provide a first example of examining the process of maintaining constructed wetlands. Additional case studies need to examine these dimensions across different contexts to build long-term adoption of DWT units, which could result in the construction of a theoretical model of a DWT innovation process managed by communities.

Decentralized WW treatment must anticipate plural valuation and devaluation of ecosystem services by not requiring anyone to compromise their physical health and social concerns about purity. Addressing the improved human-centered design of CWs, plural valuation of WW, power dynamics of community members, the current social stigma associated with the maintenance of CWs, the yuck factor, perceived benefit, increasing community WASH infrastructure and programs, and limiting antagonization of social divisions within rural communities are essential first steps before implementing any innovation or technology that treats WW for agricultural irrigation that also requires maintenance.

DATA AVAILABILITY STATEMENT

Data is not available due to ethical restrictions. Due to the nature of this research, participants of this study did not agree for their data to be shared publicly, so supporting data is not available.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Florida Institutional Review Board. The ethics committee waived the requirement of written informed consent for participation.

AUTHOR CONTRIBUTIONS

This research was completed as part of a doctoral degree program for CF. CF designed, collected, analyzed and wrote the manuscript. MM, SD, and SW all provided mentorship during research design, collection, analysis, and revised the final draft of the article. All authors contributed to the article and approved the submitted version.

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REFERENCES

Abel, N., Ross, H., and Walker, P. (1998). Mental models in Rangeland research, communication and management. *Rangel. J.* 20, 77–91. doi: 10.1071/RJ9980077

Arias-Arévalo, P., Gómez-Baggethun, E., Martín-López, B., and Pérez-Rincón, M. (2018). Widening the evaluative space for ecosystem services: a taxonomy of plural values and valuation methods. *Environ. Values* 27, 29–53. doi: 10.3197/096327118X15144698637513

Arias-Arévalo, P., Martín-López, B., and Gómez-Baggethun, E. (2017). Exploring intrinsic, instrumental, and relational values for sustainable management of social-ecological systems. *Ecol. Soc.* 22:43. doi: 10.5751/ES-09812-220443

Berbés-Blázquez, M., González, J. A., and Pascual, U. (2016). Towards an ecosystem services approach that addresses social power relations. *Curr. Opin. Environ. Sustain.* 19, 134–143. doi: 10.1016/j.cosust.2016.02.003

Bernard, H. R. (2011). *Research Methods in Anthropology: Qualitative and Quantitative Approaches*, *5th Edn*. Lanham, MD: AltaMira Press.

Bernard, H. R., and Ryan, G. W. (2010). *Analyzing Qualitative Data: Systematic Approaches*. Los Angeles, CA: SAGE .

Birt, L., Scott, S., Cavers, D., Campbell, C., and Walter, F. (2016). Member checking: a tool to enhance trustworthiness or merely a nod to validation? *Qual. Health Res.* 26, 1802–1811. doi: 10.1177/1049732316654870

Brix, H., Koottatep, T., Fryd, O., and Laugesen, C. H. (2011). The flower and the butterfly constructed wetland system at Koh Phi Phi—system design and lessons learned during implementation and operation. *Ecol. Eng.* 37, 729–735. doi: 10.1016/j.ecoleng.2010.06.035

Charmaz, K. (2014). *Constructing Grounded Theory*, *2nd Edn*. Los Angeles, CA: SAGE.

Colvin, R. M., Witt, G. B., and Lacey, J. (2015). The social identity approach to understanding socio-political conflict in environmental and natural resources management. *Global Environ. Change* 34, 237–246. doi: 10.1016/j.gloenvcha.2015.07.011

D'Andrade, R. (2005). "Some methods for studying cultural cognitive structures," in *Finding Talk in Culture: A Collection of Methods*, ed N. Quinn (New York, NY: Palgrave Macmillan) 83–104. doi: 10.1007/978-1-137-05871-3_3

Datta, A., Patil, M., and Wani, S. P. (2018). "Improving rural wastewater management," in *Cooporate Social Responsibility: Win-Win Propositions for Communities, Corporates and Agriculture*, eds S. P. Wani and K. V. Raju (Oxfordshire: CABI), 213–228.

Datta, A., Wani, S. P., Patil, M. D., and Tilak, A. S. (2016). Field scale evaluation of seasonal wastewater treatment efficiencies of free surface-constructed wetlands in ICRISAT, India. *Curr. Sci.* 110, 1756–1763. doi: 10.18520/cs/v110/i9/1756-1763

Deci, E. L., and Ryan, R. M. (2012). "Self-determination theory," in *Handbook of Theories of Social Psychology, Vol. 1* eds A. W. K. Van Lange, and E. T. Higgins (Thousand Oaks, CA: Sage Publications Ltd), 416–436. doi: 10.4135/9781446249215.n21

Denny, P. (1997). Implementation of constructed wetlands in developing countries. *Water Sci. Technol.* 35, 27–34. doi: 10.2166/wst.1997.0157

Desai, R., McFarlane, C., and Graham, S. (2015). The politics of open defecation: informality, body, and infrastructure in Mumbai. *Antipode* 47, 98–120. doi: 10.1111/anti.12117

Desai, S., and Dubey, A. (2012). Caste in 21st century India: competing narratives. *Econ. Polit. Wkly.* 46, 40–49.

Devitt, C., O'Neill, E., and Waldron, R. (2016). Drivers and barriers among householders to managing domestic wastewater treatment systems in the Republic of Ireland; implications for risk prevention behaviour. *J. Hydrol.* 535, 534–546. doi: 10.1016/j.jhydrol.2016.02.015

Díaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R. T., Molnár, Z., et al. (2018). Assessing nature's contributions to people. *Science* 359, 270–272. doi: 10.1126/science.aap8826

Doron, A. (2018). *Waste of a Nation: Garbage and Growth in India*. Cambridge, MA: United States: Harvard University Press. Available at: http://ebookcentral.proquest.com/lib/ufl/detail.action?docID=5317545 (accessed May 28, 2018). doi: 10.2307/j.ctv2867m8

Easterly, W., Ritzen, J., and Woolcock, M. (2006). Social cohesion, institutions, and growth. *Econ. Polit.* 18, 103–120. doi: 10.1111/j.1468-0343.2006.00165.x

Ellis, E. C., Pascual, U., and Mertz, O. (2019). Ecosystem services and nature's contribution to people: negotiating diverse values and trade-offs in land systems. *Curr. Opin. Environ. Sustain.* 38, 86–94. doi: 10.1016/j.cosust.2019.05.001

Friedrichsen, C. N., Daroub, S. H., Monroe, M. C., Stepp, J. R., and Gerber, S. (2019). Stakeholders' mental models of soil food value chain in the Everglades. *Geoderma* 343, 166–175. doi: 10.1016/j.geoderma.2019.02.037

Friedrichsen, C. N., Daroub, S. H., Monroe, M. C., Stepp, J. R., and Wani, S. P. (2018). Mental models of soil management for food security in Peri-Urban India. *Urban Agric. Reg. Food Syst.* 3. doi: 10.2134/urbanag2017.08.0002

Friedrichsen, C. N., Monroe, M. C., Daroub, S. H., Stepp, J. R., and Wani, S. P. (2020). Impact of mental models on constructed wetland maintenance in semi-arid India. *Water Pract. Technol.* doi: 10.2166/wpt.2020.087

Gauss, M. (2008). *Constructed Wetlands: A Promising Wastewater Treatment System for Small Localities: Experiences from Latin America*. Rochester, NY: Social Science Research Network Available at: https://papers.ssrn.com/abstract=1149070 (accessed September 28, 2020).

Giacomin, J. (2014). What is human centred design? *Des. J.* 17, 606–623. doi: 10.2752/175630614X14056185480186

Glaser, B. G., and Strauss, A. L. (1967). *The Discovery of Grounded Theory*. Chicago, IL: Aldine.

Gupta, A., Coffey, D., and Spears, D. (2016). "Purity, pollution, and untouchability: challenges affecting the adoption, use, and sustaianbility of sanitation programmes in rural India," in *Sustainable Sanitation for All*, eds P. Bongartz, N. Vernon, and J. Fox (Warwickshire: Practical Action Publishing), 283–298. doi: 10.3362/9781780449272.017

Gupta, D. (2005). Caste and politics: identity over system. *Ann. Rev. Anthropol.* 34, 409–427. doi: 10.1146/annurev.anthro.34.081804.120649

Haidt, J. (2007). The new synthesis in moral psychology. *Science* 316, 998–1002. doi: 10.1126/science.1137651

Jacobs, S., Zafra-Calvo, N., Gonzalez-Jimenez, D., Guibrunet, L., Benessaiah, K., Berghöfer, A., et al. (2020). Use your power for good: plural valuation of nature – the Oaxaca statement. *Glob. Sustain.* 3, 1–7. doi: 10.1017/sus.2020.2

Jones, N., Ross, H., Lynam, T., Perez, P., and Leitch, A. (2011). Mental models: an interdisciplinary synthesis of theory and methods. *Ecology and Society* 16:46. Available online at: http://www.ecologyandsociety.org/vol16/iss1/art46/ (accessed December 13, 2020). doi: 10.5751/ES-03802-160146

Jones, N. A., Ross, H., Lynam, T., and Perez, P. (2014). Eliciting mental models: a comparison of interview procedures in the context of natural resource management. *Ecol. Soc.* 19, 434–440. doi: 10.5751/ES-06248-190113

Kahan, D. (2010). Fixing the communications failure. *Nature* 463, 296–297. doi: 10.1038/463296a

Kearney, A. R. (2015). "3CM: a tool for knowing 'where they're at,'" in *Fostering Reasonableness: Supportive Environments for Bringing Out Our Best*, eds R. Kaplan and A. Basu (Ann Arbor, MI: Maize Books).

Kumar, D., Sharma, S. K., and Asolekar, S. R. (2016). "Constructed wetlands and other engineered natural treatment systems: India status report," in *Natural Water Treatment Systems for Safe and Sustainable Water Supply in the Indian Context: Saph Pani,* eds T. Wintgens, A. Nattorp, L. Elango, and S. R. Asolekar (London: IWA Publishing), 127–141.

Kumar, S., and Dutta, V. (2019). Constructed wetland microcosms as sustainable technology for domestic wastewater treatment: an overview. *Environ Sci Pollut Res,* 26, 11662–11673. doi: 10.1007/s11356-019-04816-9

Laugesen, C. H., Brix, H., Fryd, O., and Koottatep, T. (2010a). *The Way Forward, Mainstreaming and Other Reflections*. Reston, VA: American Society of Civil Engineers.

Laugesen, C. H., Fryd, O., Koottatep, T., and Brix, H. (2010b). *Sustainable Wastewater Management in Developing Countries: New Paradigms And Case Studies From The Field*. Reston, VA: American Society of Civil Engineers Available at: https://www.cabdirect.org/cabdirect/abstract/20103150109 (accessed September 29, 2020). doi: 10.1061/9780784409992

Laukkanen, M., and Wang, M. (2015). *Comparative Causal Mapping: The CMAP3 Method*. Surrey: Gower. doi: 10.4324/9781315573038

Lejano, R. P., and Leong, C. (2012). A hermeneutic approach to explaining and understanding public controversies. *J. Public Adm. Res. Theory* 22, 793–814. doi: 10.1093/jopart/mus001

Literat, I. (2013). "A pencil for your thoughts": participatory drawing as a visual research method with children and youth. *Int. J. Qual. Methods* 12, 84–98. doi: 10.1177/160940691301200143

LoPalo, M., Coffey, D., and Spears, D. (2019). The consequences of social inequality for the health and development of India's children: the case of caste, sanitation, and child height. *Soc. Just. Res.* 32, 239–254. doi: 10.1007/s11211-019-00323-x

Mankad, A., and Tapsuwan, S. (2011). Review of socio-economic drivers of community acceptance and adoption of decentralised water systems. *J. Environ. Manag.* 92, 380–391. doi: 10.1016/j.jenvman.2010.10.037

Møller, K. A., Fryd, O., De Neergaard, A., and Magid, J. (2012). Economic, environmental and socio-cultural sustainability of three constructed wetlands in Thailand. *Environ. Urban.* 24, 305–323. doi: 10.1177/0956247811434259

Morgan, D. L. (2018). Themes, theories and models. *Qual. Health Res.* 28, 339–345. doi: 10.1177/1049732317750127

National Sample Survey Office, Ministry of Statistics and Programme, Implementation (2016). *Swachhta Status Report*. New Delhi: Government of India. Available at: http://www.cbgaindia.org/wp-content/uploads/2016/04/Swachhta_-Status_Report-2016.pdf.

Permutt, S. D. (2011). The manual scavenging problem: a case for the Supreme Court of India note. *Cardozo J. Int Comp. L.* 20, 277–312.

Quinn, N. (2005). "Introduction," in *Finding Culture in Talk: A Collection of Methods Culture, Mind, and Society*, ed N. Quinn (New York, NY: Palgrave Macmillan), 1–34. doi: 10.1007/978-1-137-05871-3_1

Quinn, N., and Holland, D. C. (1987). "Culture and cognition," in *Cultural Models in Language And Thought*, eds D. C. Holland and N. Quinn (Cambridge [Cambridgeshire]; New York: Cambridge University Press), 3–40. doi: 10.1017/CBO9780511607660.002

Rashid, M., and Pandit, D. (2019). Determining the provision of wastewater management infrastructure in rural India from the local communities' perspectives. *Water Sci. Technol.* 79, 489–500. doi: 10.2166/wst.2019.074

Rozin, P. (2015). "Disgust, psychology of." in *International Encyclopedia of the Social & Behavioral Sciences, 2nd edn* eds J. D. Wright (Oxford: Elsevier). 6, 546–549. doi: 10.1016/B978-0-08-097086-8.26020-0

Rozin, P., Lowery, L., Imada, S., and Haidt, J. (1999). The CAD triad hypothesis: a mapping between three moral emotions (contempt, anger, disgust) and three moral codes (community, autonomy, divinity). *J. Pers. Soc. Psychol.* 76, 574–586. doi: 10.1037/0022-3514.76.4.574

Saad, D., Byrne, D., and Drechsel, P. (2017). "Social perspectives on the effective management of wastewater," in *Physico-Chemical Wastewater Treatment and Resource Recovery* eds R. Farooq and Z. Ahma (Rijeka, Croatia: BoD – Books on Demand), 253–262. doi: 10.5772/67312

Saldana, J. (2015). *The Coding Manual for Qualitative Researchers*. London: SAGE.

Saravanan, V. S., McDonald, G. T., and Mollinga, P. P. (2009). Critical review of integrated water resources management: moving beyond polarised discourse. *Nat. Res. Forum* 33, 76–86. doi: 10.1111/j.1477-8947.2009.01210.x

Schmidt, C. W. (2008). The yuck factor when disgust meets discovery. *Environ. Health Perspect.* 116, A524–A527. doi: 10.1289/ehp.116-a524

Schouten, T., and Moriarty, P. (2003). *Community Water, Community Management: From System to Service in Rural Areas.* London: ITDG Publishing. doi: 10.3362/9781780441061

Schulz, C., Martin-Ortega, J., and Glenk, K. (2018). Value landscapes and their impact on public water policy preferences. *Glob. Environ. Change* 53, 209–224. doi: 10.1016/j.gloenvcha.2018.09.015

Schulz, C., Martin-Ortega, J., and Glenk, K. (2019). Understanding public views on a dam construction boom: the role of values. *Water Resour. Manage* 33, 4687–4700. doi: 10.1007/s11269-019-02383-9

Starkl, M., Amerasinghe, P., Essl, L., Jampani, M., Kumar, D., and Asolekar, S. R. (2013a). Potential of natural treatment technologies for wastewater management in India. *J. Water Sanit. Hyg. Dev.* 3, 500–511. doi: 10.2166/washdev.2013.016

Starkl, M., Brunner, N., Amerasinghe, P., Mahesh, J., Kumar, D., Asolekar, S. R., et al. (2015). Stakeholder views, financing and policy implications for reuse of wastewater for irrigation: a case from Hyderabad, India. *Water* 7, 300–328. doi: 10.3390/w7010300

Starkl, M., Brunner, N., and Stenström, T.-A. (2013b). Why do water and sanitation systems for the poor still fail? Policy analysis in economically advanced developing countries. *Environ. Sci. Technol.* 47, 6102–6110. doi: 10.1021/es3048416

Stern, P., Dietz, T., Abel, T., Guagnano, G., and Kalof, L. (1999). A value-belief-norm theory of support for social movements: the case of environmentalism. *Hum. Ecol. Rev.* 6, 81–97.

Stern, P. C. (2000). New environmental theories: toward a coherent theory of environmentally significant behavior. *J. Soc. Issues* 56, 407–424. doi: 10.1111/0022-4537.00175

Suhardiman, D., Keovilignavong, O., and Kenney-Lazar, M. (2019). The territorial politics of land use planning in Laos. *Land Use Policy* 83, 346–356. doi: 10.1016/j.landusepol.2019.02.017

Vymazal, J. (2011). Constructed wetlands for wastewater treatment: five decades of experience. *Environ. Sci. Technol.* 45, 61–69. doi: 10.1021/es101403q

Wani, S. P. (2008). Taking soil science to farmers' doorsteps through community watershed management. *J. Indian Soc. Soil Sci.* 56, 367–377.

Wani, S. P., and Ramakrishna, Y. S. (2005). "Sustainable management of rainwater through integrated watershed approach for improved rural livelihoods," in *Watershed Management Challenges Improving Productivity, Resources and Livelihoods*, eds B. R. Sharma, J. S. Samra, C. A. Scott, and S. P. Wani (Colombo: International Water Management Institute), 39–60. Available at: http://oar.icrisat.org/6047/2/15-SP-Wani.pdf (accessed December 12, 2020).

Wani, S. P., and Sidhu, G. S. (2009). *Land Use Planning in Integrated Watershed Development Program for Improving Livelihoods*. IARI Campus, New Delhi, 154–164. Available at: http://oar.icrisat.org/5355/1/Sustainable%20Management_39-60_2005.pdf (accessed December 12, 2020).

Warren, C., and Tracy, K. (2015). *Discovering Qualitative Methods: Ethnography, Interviews, Documents and Images*, *3rd Edn*. New York, NY: Oxford University Press.

Wegner, G., and Pascual, U. (2011). Cost-benefit analysis in the context of ecosystem services for human well-being: a multidisciplinary critique. *Glob. Environ. Change* 21, 492–504. doi: 10.1016/j.gloenvcha.2010.12.008

Werellagama, D. R. I. B., and Karunaratne, S. (2011). "Engineering the wetlands," in *Wetlands for Tropical Applications*, ed N. Tanaka (Cambridge: Imperial College Press), 95–114. doi: 10.1142/9781848162983_0006

Zafra-Calvo, N., Balvanera, P., Pascual, U., Merçon, J., Martín-López, B., van Noordwijk, M., et al. (2020). Plural valuation of nature for equity and sustainability: insights from the Global South. *Glob. Environ. Change* 63:102115. doi: 10.1016/j.gloenvcha.2020.102115

Zahnd, E., and Willis, G. (2007). Questionnaire design from a cross-cultural perspective: an empirical investigation of Koreans and Non-Koreans. *J. Health Care Poor Underserved* 18, 197–217. doi: 10.1353/hpu.2007.0118

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Local Markets: Agrobiodiversity Reservoirs and Access Points for Farmers' Plant Propagation Materials

Claudia Heindorf[1]*, *Juan Antonio Reyes-Agüero*[2] *and Anuschka van't Hooft*[3†]

[1] Multidisciplinary Postgraduate Program for Environmental Sciences, Autonomous University of San Luis Potosí, San Luis Potosí, Mexico, [2] Desert Zone Research Institute, Autonomous University of San Luis Potosí, San Luis Potosí, Mexico, [3] Faculty of Social Sciences and Humanities, Autonomous University of San Luis Potosí, San Luis Potosí, Mexico

Local markets are access points to local agrobiodiversity and to part of the informal seed systems on which most small-scale farmers worldwide depend. With the urgent need for more sustainable food systems, detailed studies of the food plant diversity in local markets contribute to a better understanding of the role of local markets in a functioning rural food system. In particular, the products that farmers trade and also use for plant propagation are of interest, i.e., seeds and other propagules such as cuttings, pseudostems, rhizomes, or tubers purposes, since they represent our genetic capital for food production. This study aims to show the role of local markets as access points for plant propagation materials and their contribution to regional *in situ* conservation of local food plant resources. We analyzed the inter- and intra-specific food plant diversity of the products from local merchants in 10 markets in the agrobiodiversity rich region of the Huasteca Potosina, Mexico. We recorded 275 different food plants consisting of 99 plant species, which have a high intraspecific richness of 210 variants. The list includes 58 species that are useful for propagation. The average number of variants suitable for propagation at each market is 58.4. The results show that the different richness parameters vary within and between the inventoried markets. They correlate partially to different factors like market size and origin. We conclude that local markets in the Huasteca Potosina are important components of the rural food system by providing access to a great variety of local food plants, as well as to seeds and other propagation materials for farming. However, diversity may be threatened, because of the high average proportion of unique and rare food plants (63.5%) in the markets. Also, almost half (45.1%) of the total richness is present in <1% of the inventoried stands. Political actions are needed to maintain and promote the use and conservation of this diversity in the future.

Keywords: agrobiodiversity, food plant diversity, plant genetic resources, seed network, seed access, Indigenous people, local markets

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Banaras Hindu University, India
Luciana Porter-Bolland,
Instituto de Ecología (INECOL), Mexico

Correspondence:
Claudia Heindorf
claudia.heindorf@tutanota.com

†Anuschka van't Hooft
orcid.org/0000-0002-3742-9121

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INTRODUCTION

Markets have always been places of gathering. In Mexico, some traditional farmer markets or *tianguis* (from Nahuatl *tiankistli*) date back to pre-Hispanic times when long-distance traders and their human carriers traveled across multiple regions, providing access to natural resources from different ecological zones. The economic activities at these markets involve cultural exchange, based on traditional knowledge, of products with commercial value and social significance. As such, *tianguis* or local markets were and still are "strategic focal points for evaluating society, economy and production systems which impact the relationship between plants and people" (Linares and Bye, 2016; Colin-Bahena et al., 2018).

Local and regional *tianguis* are places where small-scale farmers market their surplus produce. Contrary to big food supply chains and supermarkets that have become the main places to purchase food in the modern food system, local markets form a vital part of the traditional food system and are important food sources for the rural population (Maxwell and Slater, 2003; Ericksen, 2008). Local markets contribute to food sovereignty by providing access to local and regional food plants produced by small-scale farmers who apply traditional management practices. These practices promote associated biodiversity in the agricultural landscapes (see Chappell et al., 2013; Fanzo et al., 2013).

Local markets also function as access points and distribution centers for local plants and seeds (FAO, 2012; McGuire and Sperling, 2016). They are the principal sources for seeds and planting materials from outside the smallholders' communities and for some crops they even represent the most important supply source (e.g., FAO, 2016; Kansiime and Mastenbroek, 2016). Local markets become even more important during stress periods that cause shortages in farmers' seed stock and in the supply from social networks (Kansiime and Mastenbroek, 2016). Furthermore, they offer a wide range of plants and seeds from different farming communities in a centralized place, which promotes local and regional seed and plant flow, and makes them especially important as seed sources in a situation of post-crisis (McGuire and Sperling, 2013). However, local markets are neglected in seed system literature. The use of planting material from local markets is not sufficiently acknowledged in formal research and the seed sectors (Sperling et al., 2020).

Two main groups of seed supply systems exist: the formal and informal or traditional systems. The formal seed sector consists of improved and certified seeds produced by scientific breeders and distributed by private companies or through governmental interventions. The informal seed sector includes mainly local varieties, which are saved and distributed through farmers' social networks and local markets (FAO, 2016). The informal seed sector still plays an important role in seed access and distribution in the developing world, especially for the 475 million small farms (<2 ha) that belong to family farmers of a total of 570 million farms worldwide (Lowder et al., 2014). Different studies show that most farmers (75–90%) in the Global South depend primarily on seed and planting materials from the informal seed system (Almekinders et al., 1994; Sperling and McGuire, 2010; Poudel et al., 2015), as they obtain seed and planting materials from their own stock or from neighbors, relatives, and local marketplaces. Farmer seed circulation networks, which include local markets, facilitate access to new varieties and landraces (McGuire and Sperling, 2016). Since the beginning of agriculture, trading networks enable the dissemination of new crops, and their related technical knowledge. They even boost domestication processes, e.g., those reported for the case of Nubian cotton, when the Roman trade of cotton from India encouraged Nubian farmers to domesticate their own local cotton (Van der Veen, 2011; Meyer et al., 2012).

Fostering agroecological development and promoting the transition processes to more sustainable agricultural production involves access to local seed sources (Sperling and McGuire, 2010). Next to conditions such as access to agroecological knowledge, access to land, governmental support, and solidarity markets (FAO, 2018b; Anderson et al., 2019), agroecological transformation and scaling depend on native or local seeds as a non-replaceable good linked to multiple dimensions of the agroecosystem (Chable et al., 2020). One main advantage of autochthonous plant propagation resources is their optimal fitting to the local cultural and environmental setting with its particular biotic and abiotic conditions because they were keenly selected over time and coevolved with farmers' needs and preferences (Cleveland et al., 1994). A further advantage is the propagation of these local seeds and plants by the farmers themselves. This strengthens farmers' seed sovereignty, autonomy, and flexibility in decision making, while at the same time reducing their dependence on external inputs like new seed materials, fertilizers, and chemicals for pest control (Cleveland et al., 1994; Adhikari, 2014). The use of local seeds contributes to the conservation and evolution of traditional knowledge on farming management practices but also of the preparation and processing of traditional foods and beverages. Traditional food plant diversity keeps agroecological knowledge vivid and evolving. In sum, local plant materials and seeds are the fuel for social-ecological networks in agricultural societies in which agroecology is practiced, which is necessary for agroecological scaling (García López et al., 2019).

Mexico counts over four million family farms, representing 78.6% of the total agricultural production units. Most of these family farms (73.0%) are dedicated to agricultural production. Here, Indigenous and other small-scale farmers manage a high diversity of food plants in integrated agricultural-forestry systems, mainly providing subsistence diets (Altieri, 2002). Farmer and community-based seeds still play a central role in these agricultural-forestry systems, even when the country has an advanced formal seed development and supply system. Formally certified seed supply is mainly limited to some selected key crops like maize and bean. Commercial seeds are often not well accepted by the local farmers as they show a weaker performance regarding adaptation to local environmental conditions and management practices. Also, they are considered to have a less favorable taste and flavor (Bellon, 1996; Louwaars and de Boef, 2012; Coomes et al., 2015).

Despite the cultural importance and the diversity of products offered in the local markets, detailed inventories of market products are scarce and focus on medicinal plants and some selected food groups (e.g., Martínez-Moreno et al., 2006; Hernández-Rico and Moreno-Fuentes, 2010; Juárez Hernández et al., 2014). In Mexico, but also worldwide, complete and recent surveys that include information on intraspecific diversity in local markets are still missing. This hinders the understanding of "the role of these markets" in the access to food plant diversity in general and to plant propagation resources.

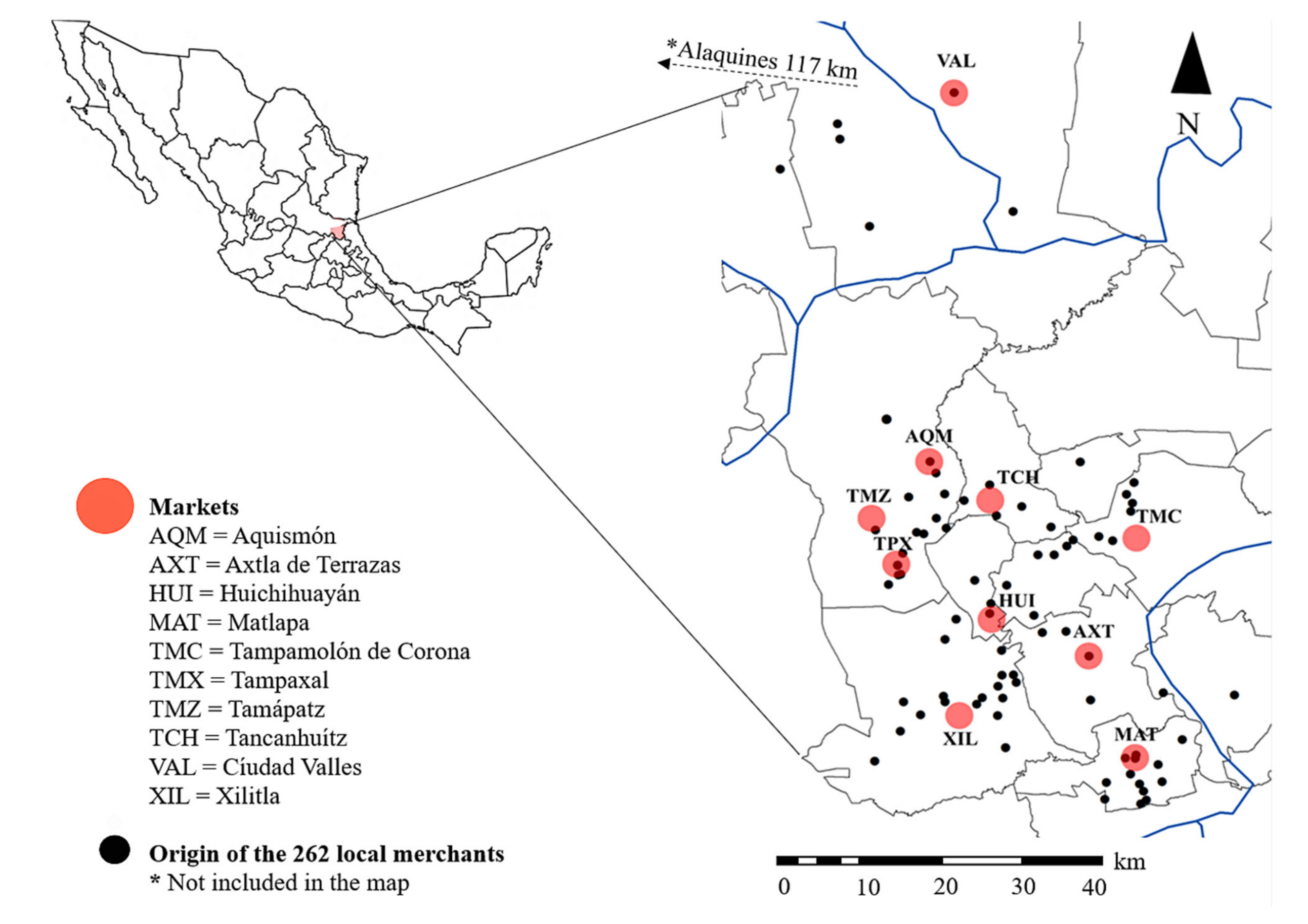

FIGURE 1 | Location of the markets in the Huasteca Potosina included in this study and the communities of origin of the local merchants.

This study investigates the contribution of rural markets to the use and *in situ* conservation of local food plant resources. Local food plant resources include native and non-native food plant species, as both are part of the local diet and traditional knowledge system. Based on a case study, we show the reservoir of food plants on the *tianguis* in the Huasteca Potosina, Mexico, displaying their role as an important supply source of planting materials and seeds for local farmers. We analyzed the inter- and intraspecific food crop diversity of the commercialized products in 10 local markets. By "products," we mean food plant species and variants that are merchandised in their complete natural form or parts (seeds, leaves, and fruits). We did not include processed foods. Emphasis was put on food plant propagation resources.

METHODS

Site Selection and Data Collection

For this study, we selected 10 local rural markets mentioned as important seed sources by key informant farmers in a previous study (Heindorf et al., 2019). All these local markets are situated in the Huasteca Potosina region in the southeastern part of the federal state of San Luis Potosí in Mexico (**Figure 1**). The Huasteca Potosina is an environmentally heterogeneous tropical mountainous region covering different vegetation types (**Table 1**). Most small-scale farmers in the Huasteca Potosina apply traditional management practices and manage a highly diverse agroecosystem. They usually do not depend on external inputs like fertilizers, pest control, or machinery but manage their agroecosystem based on agroecological methods and traditional knowledge. The use of native seeds is predominant (Heindorf et al., 2019).

Most of the markets included in the study belong to municipalities where the population is predominantly of Tének (Huastec Mayan) origin, yet marketplaces are arenas for social interaction between members of various ethnic groups (**Table 1**). Due to the seasonal effect in the variety of products, each of the 10 markets was visited twice, the first time during the rainy season (mainly May–August) and again at the end of the rainy season and the beginning of the dry season (mainly in November–May). At each market, all stands were counted and assigned to different stand types depending on the product category offered (e.g., fruits and vegetables, medicinal and ornamental plants, fish and seafood). In our study, a stand is a spot where people sell their

TABLE 1 | Characteristics of the research sites.

Markets inventoried	Ten local rural markets: AQM, Aquismón; AXT, Axtla de Terrazas; HUI, Huichihuayán; MAT, Matlapa; TMZ, Tamápatz; TMC, Tampamolón de Corona; TMX, Tampaxal; TCH, Tancanhuitz; VAL, Ciudad Valles; XIL, Xilitla.
Distance between the markets	From North to South: 92 km. (Ciudad Valles—Matlapa)
	From West to East: 47 km. (Tamápatz—Tampamolón de Corona)
Dominant potential vegetation types (altitude)	Tropical deciduous forest (0–300 m) Tropical rainforest (300–800 m)
	Cloud forest (800–1,200 m), and
	Oak and pine forest (>1,200 m)
Ethnic groups	Tének (main ethnic group), Nahua, and Xi'iuy, and non-Indigenous population
Land use systems	*Milpas* (polyculture maize fields)
	Cañaverales (sugarcane fields)
	Agroforestry systems: *Fincas* (plantations that focus on coffee production), *Te'loms** (patches of agroforestry systems inside the forest and mixed with perennial and semi-perennial crops), Home gardens (agroforestry systems around the housing complex), *Huertas* (fruit tree plantations)
Local merchants interviewed	262 (most of them Tének); they live in the communities close to the local markets and sell locally produced fruits and vegetables. One local merchant is equal as one local stand.
Non-local merchants	Not included in this study; they sell products from outside the region.

**Tének name.*

products, which can be either a formal market stall, a place on the ground, or in the streets.

As the research focused on the rural markets as access points to local seed and plant variants, we included only local merchants and their products in this study. By local merchants, we refer to people from the surrounding rural communities who offer fruits and vegetables cultivated in their managed agroecosystem complex. Some offer the products from other farmers of their communities as well. Also, they may resell regional products purchased in urban centers. By non-local merchants, we refer to people who sell mainly food and products produced outside the region. Most of the non-local merchants do not live in the surrounding rural communities. Local merchants usually cannot afford to rent fixed market stalls with furniture to accommodate their products (**Table 1**, **Figure 2**). Instead, they display their products on wooden boxes or blankets on the ground or walk around to offer their merchandise (Pérez Castro, 2005). After a random selection process, we inventoried 63.3% (SD = 17.6) of these stands or selling points.

We interviewed 262 local merchants to obtain general socio-demographic data and information on the origin of their products. We recorded the edible inter- and intraspecific food plant diversity of each of their stands, together with the local names and descriptions. Local collaborators accompanied us during the market visits and interviews, as they are acquainted with local varietal descriptors and have expert knowledge on local food plant diversity. In several cases, interviews were exclusively held in Tének because local merchants were more familiar and at ease with their Indigenous language.

For some key crops in the region, planting material is not available at the local markets (e.g., banana cuttings). Likewise, not all food plants at these markets serve as propagation materials (Sperling, 2008). To show the contribution of local markets in the procurement of seeds and plant products and information about the suitability as plant propagation materials, we considered data from our main research project with 33 local farmers about the used plant propagation materials and the provenance of more than 1,700 inventoried food plants and their variants (Heindorf et al., 2019, in preparation).

Data Analysis

Our data on food plant diversity from the local merchants comprise both intraspecific crop diversity and total food plant diversity. Intraspecific diversity includes all food plants that have more than one recognized variant in the markets. We also analyzed market products that serve as propagation materials (e.g., seeds and other propagules).

We calculated food plant diversity for each market based on the Simpson Diversity Index (Magurran, 1991).

$$D = 1 - \sum pi^2$$

To calculate relative abundance (pi), we used data on the presence-absence of plant species in the inventoried stands (Evangelista et al., 2012):

where $pi = \frac{ni}{N}$

n = number of stands per market where the species i was recorded.

N = number of all stands per market.

Then, we calculated the Simpson Diversity Index separately for farmers' recognized variants (D_{FVar})

where $pi = \frac{ni}{N}$

N = number of all stands per market.

n = number of stands per market where the variant i was recorded,

as well as for species of the seed and plant propagation materials (D_{Prop})

where $pi = \frac{ni}{N}$

N = number of all stands per market.

n = number of stands per market where the species of the seed and plant propagation materials i was recorded.

We created a rank-frequency curve to show species distribution. Linear regressions of diversity parameters, market size, and the number of local merchants complement the results. Furthermore, we present clustering heat maps to visualize species composition within each market and show the similarity of species composition and distribution among the 10 markets. We used Ward's method algorithm and Euclidean distance measure. The heat maps were modeled with the "pheatmap" package in R 4.01 (https://cran.r-project.org/).

FIGURE 2 | Examples of stands with products offered by local merchants in the rural markets of the Huasteca Potosina.

Additionally, we used Sigmaplot 14.0 (https://systatsoftware.com/products/sigmaplot/) and Past 3.20 Software (*https://folk.uio.no/ohammer/past/)* to calculate the diversity index and correlations.

RESULTS

In the Huasteca region, *tianguis* are local markets that operate on a rotating basis on separate days of the week in each location without competing with each other; on Sundays in the more important localities such as Ciudad Valles, and distributed over the rest of the weekdays in smaller places. In this regional market system, the most important local markets are centers for resource concentration and redistribution where products from different ecological zones converge. The smaller markets are less diverse and depend upon the more important ones for product provision.

Local markets are also called *plaza*, as they are often installed in the town's main square. In the Tének language, they are named *bichow* (lit. town, city) or *nujumtaláb*. Besides their importance for purchasing fruits and vegetables, markets are essential places to buy products that are not locally produced and thus connect with the globalized economic system. They are selling points for cheap, low-quality globalized industrial goods, such as sunglasses, jewelry, toys, music CDs, and plastic articles (Pérez Castro, 2005), presented next to traditional *comales* (clay or metallic griddles), candle holders, palm fiber fans, and other local handicraft products. Also, one can find stands with imported second-hand clothing and shoes, haberdashery products, or fabrics. Similarly, the agro-livestock sector offers local produce where people sell *piloncillo* (brown sugar), live birds, aromatic herbs, dairy products, and a great variety of chilis, among many other items (Pérez Castro, 2007). In small on street restaurants and stands on the market, women prepare traditional regional foods and beverages such as *atole*, sweet corn tamales, and *zacahuil* (the largest tamal of Mexico, of about 150–200 portions prepared as a special dish during festivities).

General Description of the Local Markets

The 10 markets are characterized by numerous stands with different products (**Figures 1**, **3**). They have an average number of 252.1 stands, ranging from 70 in Tampaxal to 538 stands in Ciudad Valles, the biggest and most important market town in the Huasteca Potosina (**Table 2**). The others include marketplaces in municipal capitals but also a relatively large one in a village along the main road (Huichihuayán) and two more in smaller villages in remote areas (Tampaxal and Tamápatz). The highest proportion of stands include clothing, shoes, and accessories (20.5%) (**Figure 3**). Still dominating the rural market character (37.3%) are stands that offer agricultural goods (including products from local merchants, medicinal and ornamental plants, seasonings, coffee, and seeds). The average proportion of stands run by local merchants, who offer mainly local alimentary agricultural products, is 17.7%. Stands with

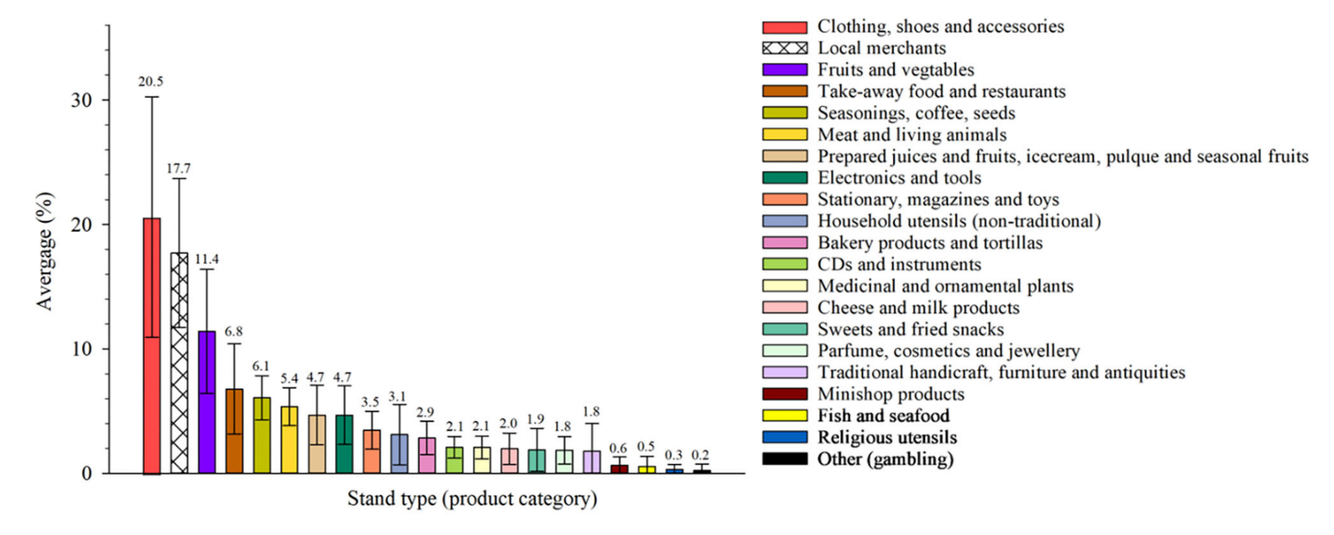

FIGURE 3 | Mean of the proportion (%) of stand types in 10 rural markets in the Huasteca Potosina.

commercial fruits and vegetables, offered by non-local sellers, comprise 11.4%. However, the high SD-values indicate that market structure and composition vary from market to market. For example, in Aquismón, the proportion of local merchants is the lowest (7.7%), whereas in Huichihuayán, the proportion of local merchants exceeds a quarter of all stands (25.6%) (**Figure 3** and **Table 2**). Regarding the proportion of local stands, linear regression shows a significant correlation between the number of total stands and the number of stands run by local merchants ($R = 0.89$ with $P < 0.001$).

General Description of the Local Merchants

The local merchants offering local agro-alimentary products have an average age of 48 years (SD = 16.1). Most of them are of Indigenous origin, with a majority of Tének (61.1%), followed by Nahuas (31.3%), and a minority is of non-Indigenous origin (7.6%). The proportion of women is almost two-third (64.5%) and the average distance from the merchant's community to the markets is 20.5 km (SD = 20.6 km), ranging from <1 to 178 km. On each market, the local merchants come on average from 12.3 (SD = 5.2) communities. During one market day, each local merchant sells an average of 7.43 (SD = 4.12) different products for a value of 674.0 MXN (28.2 US-Dollar) with an SD-value of 509.1 MXN and ranging from a minimum of 26 MXN to 2,970 MXN. On average, the local merchants go out to sell 1.89 (SD = 1.72) times each week. Most of them (82.4%) sell their products on one single weekly market. For the great majority of them, this is their only income opportunity (94.3%).

Food Plants Provenance

Regarding the provenance of the recorded products, over three quarters (77.3%) are cultivated by the local merchants themselves, which shows the predominance of direct marketing (**Figure 4**). The most important production systems are the milpas and home gardens, where almost two-thirds (66.2%) of the products derive. Both systems are the principal production units for grains and regional staples. For example, most maize and bean variants are produced in the milpa fields. Maize, if not bought in other places, derives exclusively from the milpa fields (71.1%), as well as 74.4% of all the bean species (*Phaseolus* spp. and *V. unguiculata*). Other species that are mainly produced in the milpas include vegetables like tomato (*Solanum lycopersisum*, 87.2%), winter squash (*Cucurbita moschata*, 82.6%), edible weeds like amaranth leaves (*Amaranthus hybridus*, 76.9%), chilis (*Capsicum* spp. 55.9%), and nopal cactus (*Nopalea cochenillifera*, 55.6%).

Typical market products that are cultivated in the home gardens include regional staples like chayote (*Sechium edule*, 45.7%) and fruits like banana and plantains (*Musa* sp., 50.8%), and mango (*Mangifera indica*, 69.2%). The *te'loms* and fincas are the main suppliers of coffee (*Coffea* sp., 51.4%) and more than 80% of the recorded wild chili species (*C. annuum* var. *glabriusculum*). Crops that are not very common in the region, like chard (*Brassica oleracea*, 95.5%) or beetroot (*Beta vulgaris*, 80%), cultivated in more temperate zones, are purchased in other places outside the merchants' village or directly on the market from non-locals. The same applies to recently introduced crops like litchi (*Litchi chinensis*, 91.7%).

Local Merchants and Food Plant Diversity

The total food plant diversity on the 10 local markets covers 275 plant types consisting of 99 different species. They include 65 plant species with no intraspecific diversity (only one variant) and 34 species with ≥2 variants. The total number of variants that belong to species with intraspecific diversity is 210. The average number of variants per species is 2.12. Some species have a distinctly higher number of variants than average. These species include chayote *S. edule*, 51 variants), winter squash (*C. moschata*, 25), mango (*M. indica*, 12), and scarlet runner bean

TABLE 2 | Inter- and intra-specific richness and diversity of local food plant diversity in 10 rural markets of the Huasteca Potosina.

	Total	AQM	AXT	HUI	MAT	TMZ	TMC	TMX	TCH	VAL	XIL	Mean	SD
Stands													
Total	2,521	326	124	170	273	110	238	70	242	538	430	252.1	147.6
Local merchants	442	25	25	44	55	25	27	7	52	105	77	44.2	29.3
Richness													
Total	275	81	76	87	98	53	74	21	117	147	119	87.3	35.7
Plant species	99	34	31	30	45	30	40	16	52	60	60	39.8	14.4
Intraspecific	210	65	64	77	77	43	58	15	94	116	86	69.5	27.9
Propagation sp.	58	18	14	20	24	17	24	10	31	35	37	23.0	9.0
Diversity													
***D*-Simpson**													
D_{Total}		0.98	0.98	0.98	0.98	0.98	0.98	0.95	0.98	0.99	0.98	0.98	0.01
D_{FVar}		0.97	0.98	0.98	0.98	0.97	0.97	0.93	0.98	0.99	0.98	0.97	0.02
D_{Prop}		0.89	0.86	0.91	0.91	0.92	0.92	0.89	0.94	0.94	0.93	0.91	0.02

D_{FVar}, Farmer recognized variants; D_{Prop}, Plant species that are used as propagation material. SD, Standard deviation. Local markets: AQM, Aquismón; AXT, Axtla de Terrazas; HUI, Huichihuayán; MAT, Matlapa; TMZ, Tamápatz; TMC, Tampamolón Corona; TMX, Tampaxal; TCH, Tancanhuítz; VAL, Ciudad Valles; XIL, Xilitla.

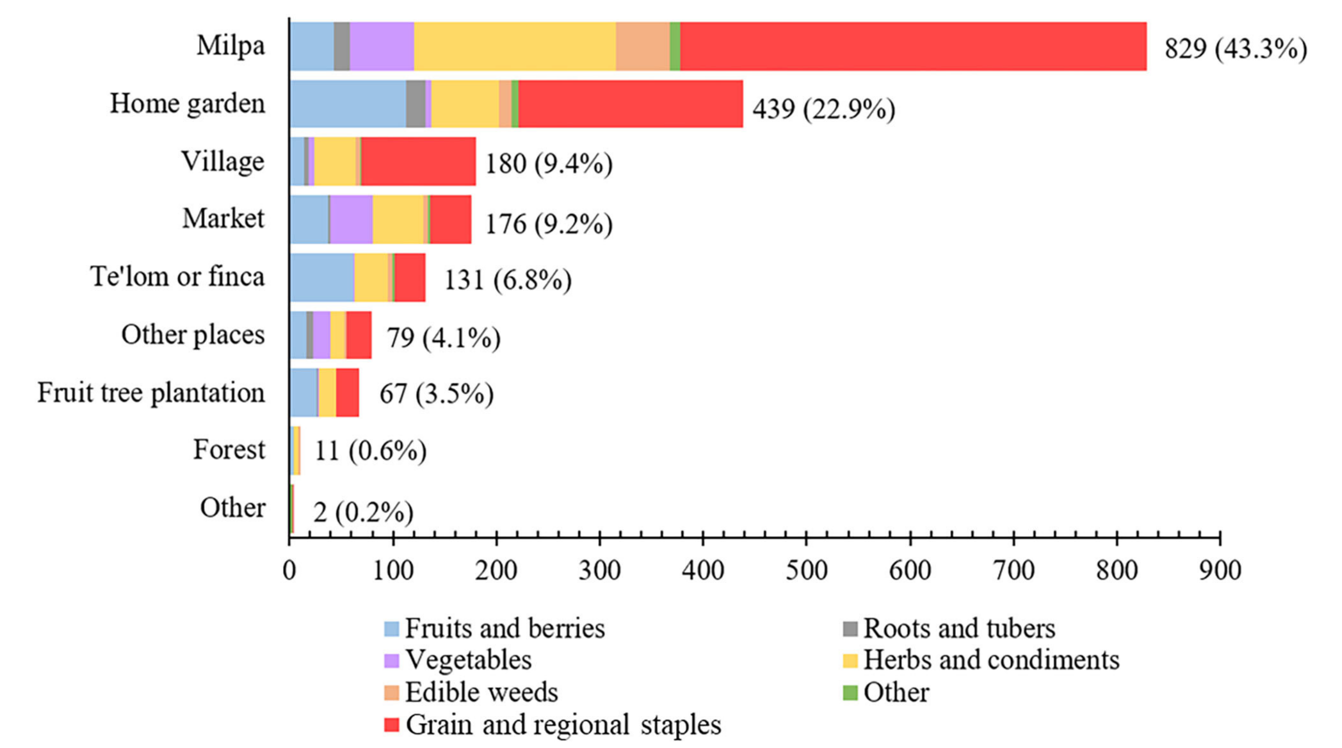

FIGURE 4 | Provenance of the products from local merchants in 10 rural markets in the Huasteca Potosina.

(*P. coccineus*, 11). Almost a third of all recorded plant species are fruits including berries (30.3%), and a quarter belongs to herbs and condiments (25.3%). We also recorded eight edible weed species (**Figure 5A**). Results differ when including the records of variants. In this case, grains, and regional staples (46.7%) dominate the product range of the local merchants, followed by herbs and condiments (21.7%), and fruits and berries (16.4%) (**Figure 5B**).

The average number of total plant types recorded per market is 87.3. This includes an average of 39.8 plant species. Worth mentioning is the high average of intraspecific richness with 69.5 variants per market (**Table 2**).

The high SD-values and the fact that the markets differ in size and the number of local merchants (**Table 2**) lead to suggest a correlation between these parameters and richness measures. Indeed, there is a statistically significant correlation between the

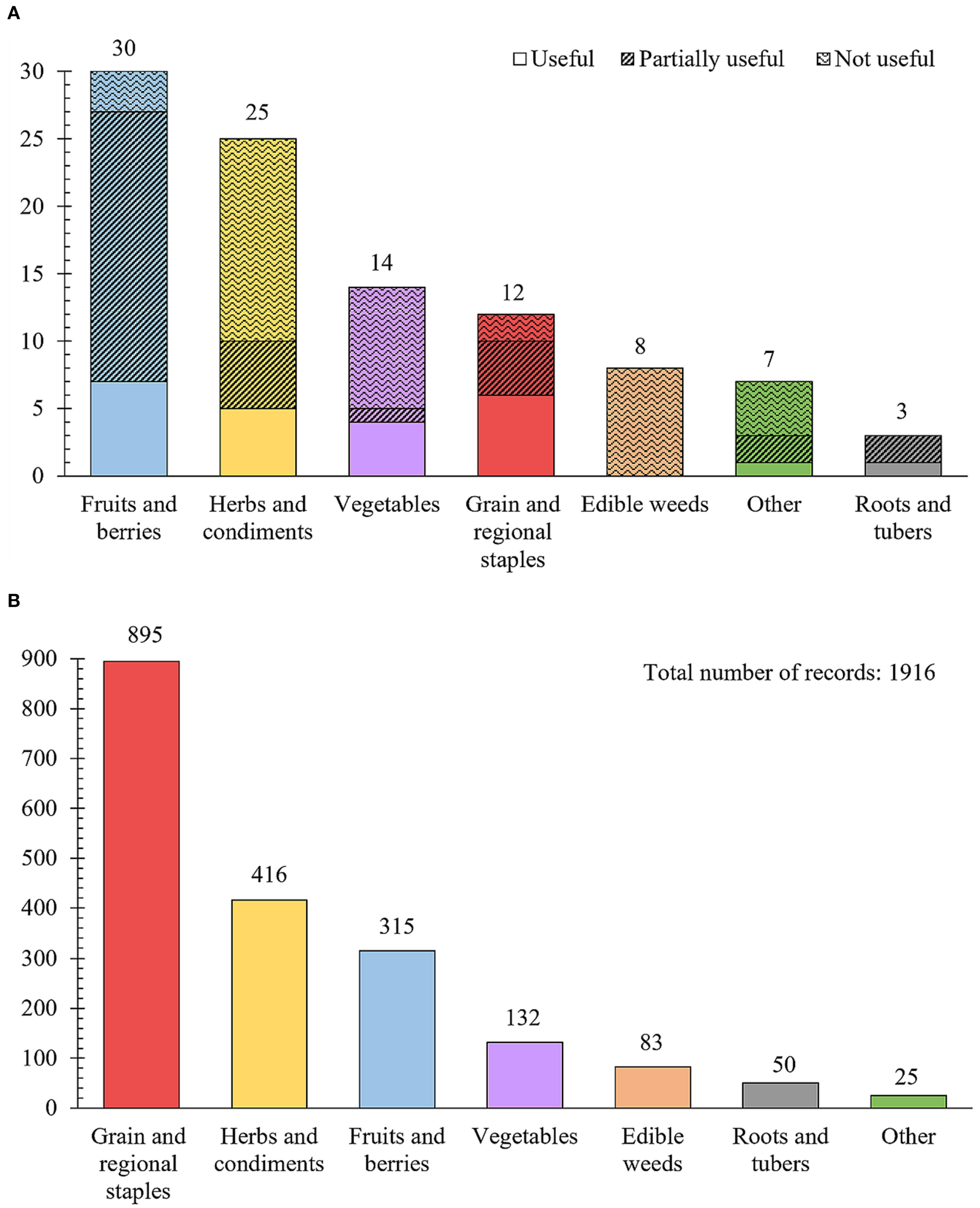

FIGURE 5 | (A) Usefulness of all documented plant species as propagation material. **(B)** Categories of edible plant species and variants from local merchants in 10 rural markets in the Huasteca Potosina. Note that the categories and grain and regional staples also include species like *Sechium edule* and *Nopalea cochenillifera*.

total number of stands (market size) and the total richness of food plants of the local merchants ($R^2 = 0.74$ and $P < 0.01$). The correlation is less strong for intraspecific richness ($R^2 = 0.64$ and $P < 0.01$) but is still statistically significant. However, bigger markets do not necessarily provide access to a greater number of plant propagation materials ($R^2 = 0.37$ and $P < 0.1$). Apart from market size, the number of local merchants is also related to the different richness parameters. A statistically significant and strong correlation exists between the number of local merchants and both the recorded total richness ($R^2 = 0.85$, $P < 0.001$)

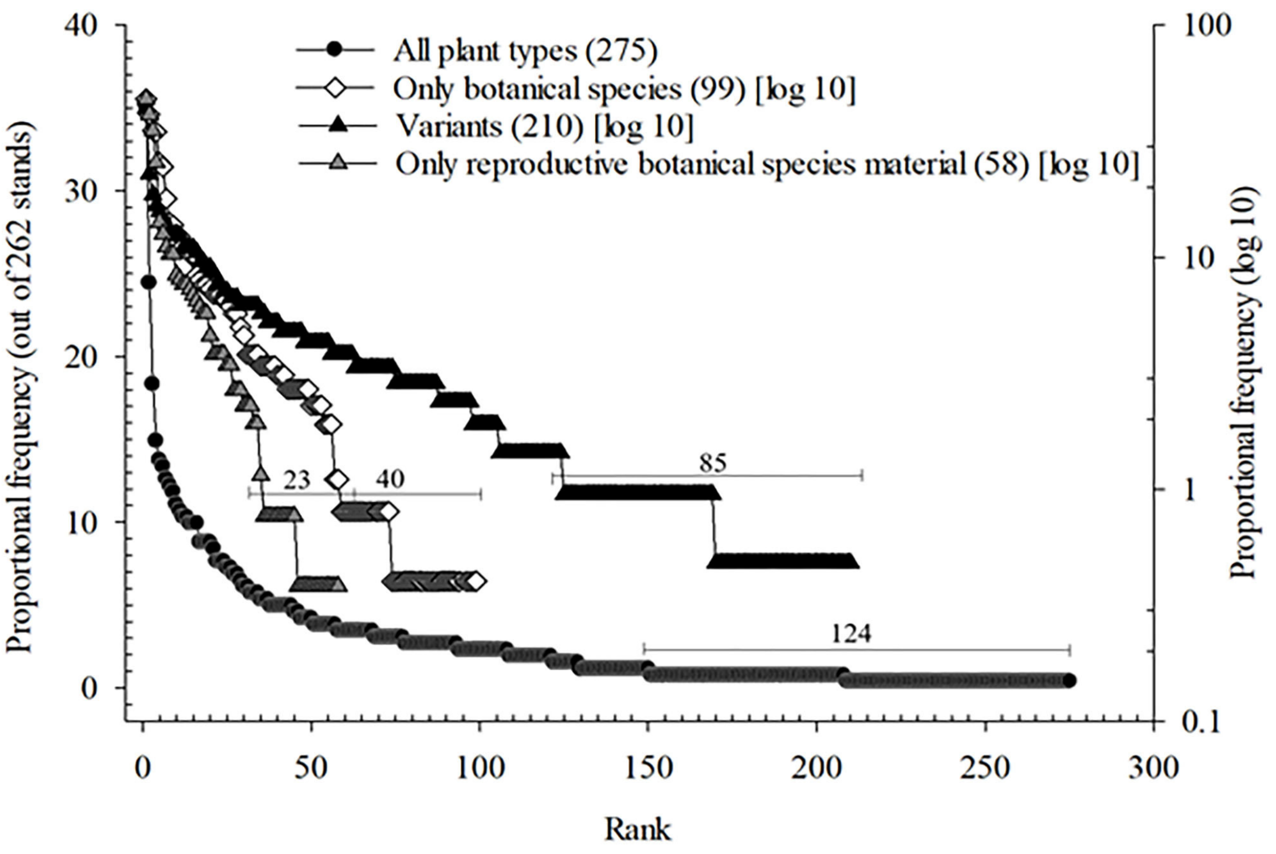

FIGURE 6 | Proportional rank-frequency curve of different richness parameters of the food plants from local merchants in 10 markets in the Huasteca Potosina.

and intraspecific richness ($R^2 = 0.80$, $P < 0.01$). The number of local merchants and the richness of seeds and plants used for propagation showed a lower correlation ($R^2 = 0.50$, $P < 0.05$). The number of different home localities of the local merchants and where they bring most of their products from does not correlate with the number of total richness ($R^2 = 0.27$, $P < 0.2$) nor with the propagative materials offered ($R^2 = 0.26$, $P < 0.2$).

The rank frequency curve demonstrates that almost half of all registered food plant types (124, 45.1%) was found in <1% of the 262 inventoried stands. Concerning the diversity subclasses, ∼40% of the variants, botanical species, and species useful for propagation is offered by <1% of the local merchants (**Figure 6**).

Of all recorded plant types, a few very frequent species and variants include the local coriander variant (*Coriandrum sativum*), found in more than a third of all stands (35.1%), followed by mint (*Menta* aff. *spicata*, 24.2%), bird chili variant (*C. annuum*, 18.3%), and wild chili (*C. annuum* var. *glabriusculum*, 14.8%). Regarding the species with propagation potential, *S. edule* (48.1%) is the most representative species available on the markets, followed by coriander (*C. sativum*, 41.2%) and chili (*C. annuum*, 35.1%). Nopal (*Nopalea cochenillifera*, 34.7%) is the most frequent species without propagation potential, for only its tender cladodes are sold.

A list of all recorded food plant species and variants is also presented in the heatmap cluster in **Supplementary Material 1**. The heatmap shows three main clusters and probably two reasons for their formation: market size and the local merchants' community of origin. The biggest markets, Ciudad Valles (VAL) and Xilitla (XIL), are clustered together as well as medium-sized markets like Tancanhuitz (TCH) and Axtla de Terrazas (AXT). However, one market, Aquismón (AQM), is very different in terms of its composition. This can probably be explained by the fact that most of its local merchants come from only one community, Jom te' Eureka, and these merchants were not present in the other markets. This would also explain why Tamápatz (TMZ), even though a relatively small market, forms part of the cluster of Xilitla and Ciudad Valles, because several of the local merchants who offer the products on these markets share the same community of origin. The heatmap also shows that only a few food plant species share a high abundance in almost all markets (e.g., *S. edule*) while many others have low abundance in each market and a low overall distribution (e.g., *Ardisia venosa*), which underlines the results of the rank-frequency curve. Interestingly, some exceptional cases occur, like the markets in Tampaxal (TMX) and TMZ, where *S. edule* and *Coffea* sp. were not recorded even though they are very frequent on all the other markets.

TABLE 3 | Distribution of the food plant species useful for propagation in the markets in the Huasteca Potosina.

	AQM	AXT	HUI	MAT	TMZ	TMC	TMX	TCH	VAL	XIL	Mean (SD)
Plant species	18	14	20	24	17	24	10	31	35	36	23.0 (9.0)
FSpe	4	4	4	7	3	5	2	9	12	17	6.7 (4.5)
FVar	53	61	66	64	34	45	10	81	98	72	58.4 (23.5)
Total*	58	65	70	71	37	50	12	90	110	89	65.1 (28.2)
Unique											
FSpe	1	2	2	1	23	3	2	3	8	9	5.4 (6.4)
FVar	28	40	38	29	2	30	10	45	37	33	29.2 (12.8)
Total	29	42	40	30	25	33	12	48	45	42	34.6 (10.4)
Rare											
FSpe	3	2	2	6	1	2	–	6	3	8	3.3 (2.4)
FVar	21	20	27	33	8	14	–	34	60	39	25.6 (16.3)
Total	24	22	29	39	9	16	–	40	63	47	28.9 (17.8)
Common											
FSpe	–	–	–	–	–	–	–	–	1	–	0.1 (0.3)
FVar	4	1	1	2	3	1	–	2	1	–	1.5 (1.2)
Total	4	1	1	2	3	1	–	2	2	–	1.6 (1.2)

SD, Standard deviation. Local markets: AQM, Aquismón; AXT, Axtla de Terrazas; HUI, Huichihuayán; MAT, Matlapa; TMZ, Tamápatz; TMC, Tampamolón Corona; TMX, Tampaxal; TCH, Tancanhuítz; VAL, Ciudad Valles; XIL, Xilitla.
FSpe, farmers' and merchants' locally recognized species with no documented intraspecific variation (<2 variants per plant species).
FVar, farmers' and merchants' locally recognized variants.
**FSpe + FVar, Total inter- and intraspecific food plant richness.*
Unique, presence in one stand of the market, rare = in <30% of the stands per market, common = in 30–60% of the stands per market.

The Simpson diversity index confirms and complements the aforementioned results (**Table 3**). The values are high, especially for the total of all edible plant types. It indicates that almost no dominant species or variants were inventoried. In the case of the diversity of species with propagation potential, the average value is slightly lower and can be explained by the fact that some species, for example, *S. edule* and *C. moschata*, are more frequent on each of the markets (see also **Supplementary Material 1**, **Figure 7**), which decreases species evenness.

Diversity of Plant Propagation Materials

More than 1,700 data points registered from food plant species and variants of 33 farmers in the region (Heindorf et al., 2019, in preparation) testify that almost half of them derived from the farmer's own stock (46.2%), more than a third from different sources in the farmer's village (33.3%), and 16.7% from outside the village. Most of the seeds and plants from outside the village were obtained from local markets (53.8%), where local merchants were the main sources for seed and plant materials (92.9%). The number of species obtained from local markets for propagation purposes was 50. The species with the highest level of occurrences within this group include *Phaseolus coccineus* (36.7%), *Vigna unguiculata* (36.0%), *Carica papaya* (30.4%), *Persea americana* (19.6%), and *Zea mays* (17.0%).

Our market inventory data show that not all products sold by the merchants serve as plant propagation materials. More than half of the 99 plant species recorded can be used partially (27.7%) or in all cases (30.3%) as plant propagation materials (**Figure 5A**). This depends mainly on the type of processing. For example, cooked chayote (*Sechium edule*) plants and fresh maize (*Zea mays*) cobs cannot be used for propagation purposes, whereas the uncooked chayote plants and dried maize seeds maintain their propagation potential, thus both species were considered as partially useful for propagation. The proportion of useful and partially useful material is highest for fruits and berries (90%) and grains and regional staples (83.3%). Edible weeds like *Ipomoea* spp. cannot be propagated (0%) if purchased on the markets, neither can many vegetables and herbs and condiments (**Figure 5A**).

The average number of species useful for propagation per market is 23.0. The average intraspecific richness of 58.4 for these species clearly exceeds the number of 6.7 for species with no intraspecific diversity. The average number of unique species and variants with propagational use within the same market is 34.6. The number of rare species and variants is slightly lower with 28.9. Only a few common food plants (1.6) that can be used as plant propagation materials can be found in more than 60% of the stands from the local merchants (**Table 3**). The clustered heat map (**Figure 7**) illustrates which species with intraspecific diversity have the highest coverage on each market. It shows that only a few species, e.g., *S. edule* or *C. annuum*, are frequent and abundant on all the markets. An exception is the market of Tamapaxal (TMX), which does not show the presence of *S. edule* or a higher abundance of *C. annuum*, which explains why this market forms a completely separated cluster. It is also the market with the lowest total number of species with propagation potential and does not show a high number of variants. There are two other main clusters with up to five end groups. Each endgroup includes markets with similar species composition and species distribution. For example, the markets of Tamápatz

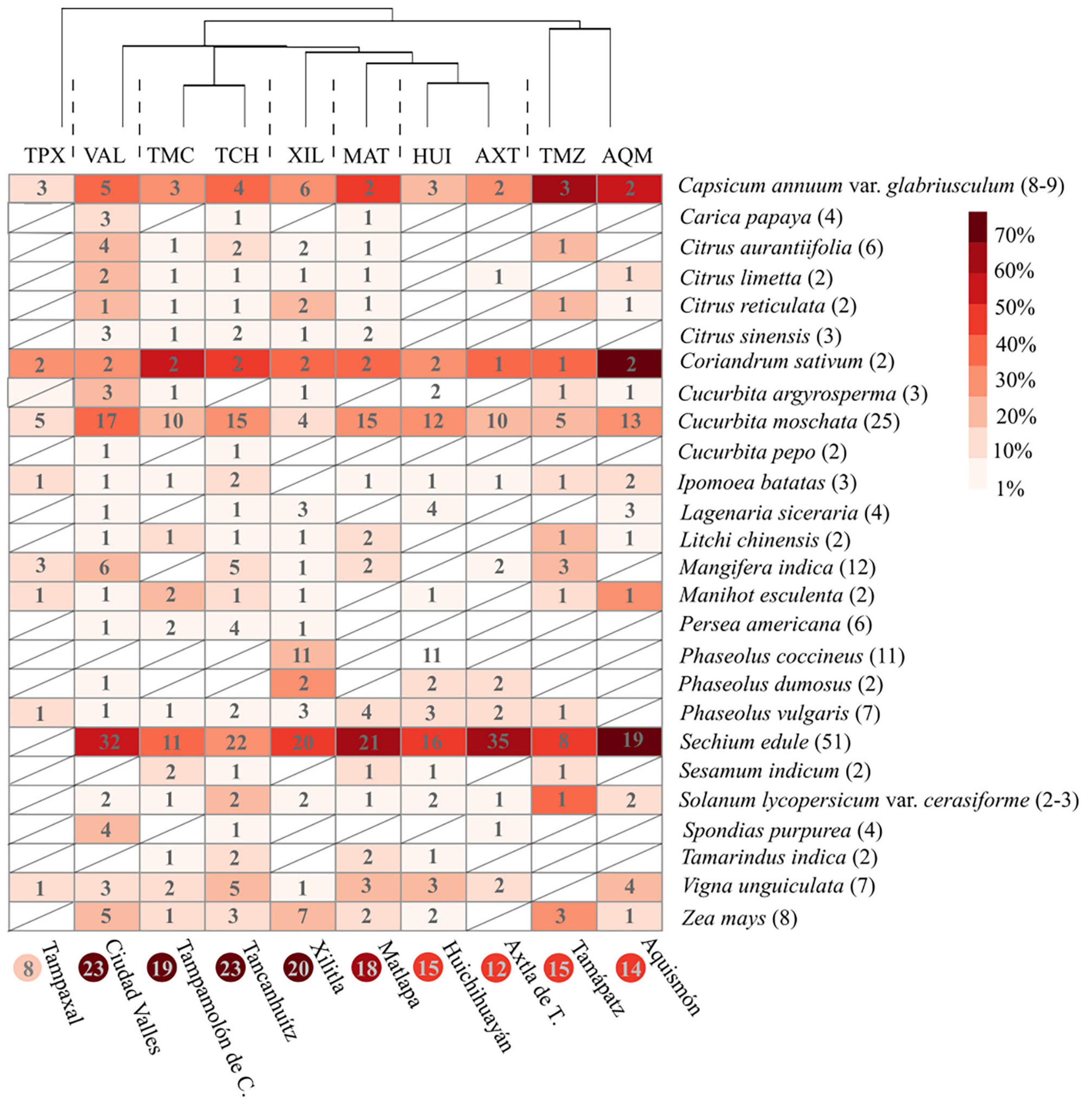

FIGURE 7 | Heatmap cluster displaying the proportion of local merchants in 10 local markets of the Huasteca Potosina who offer species with intraspecific diversity that are used as propagation material. Clustering heat maps were created using Ward's method algorithm and Euclidean distance measure. The dashed lines separate the end groups. The intensity of the red fillings according to the scale shows the proportional abundance. The number in the quadrants represents the number of total variants of the listed species at each market, and the number in brackets the total number of variants in the 10 markets. The numbers below the diagram refer to the total number of species with intraspecific diversity and propagation potential in each market.

(TMZ) and Aquismón (AQM) share a high proportion of *C. annuum*. Huichihuayán (HUI) and Axtla de Terrazas (AXT) belong to the same end groups, as both markets have a lower richness and frequency of some fruit species (e.g., *Citrus* spp. and *Persea* spp.) and tubers (*Manihot esculenta*) but are the only places where all the bean species are available. However, the proportion of local merchants who offer *P. dumosus* and *P. coccineus* is highest for Xilitla (XIL). The other end groups of this cluster offer most of the propagation materials, ranging from 18 to 23 species. Moreover, it is shown that the biggest market, in Ciudad Valles (VAL), has the highest proportion (40%) of local merchants who sell *Cucurbita moschata*. However, **Figure 7** also demonstrates that the value of the proportional abundance of a species does not necessarily mean that the varietal diversity of the species is equally high. For example, Aquismón has the highest proportion of local merchants offering *S. edule* (71.4%), but only 19 variants, whereas in Axtla de Terrazas chayote is offered by less local merchants, yet with a total of 35 recorded variants. A similar case is Ciudad Valles with 32 chayote variants. Results of linear correlations of the number of local merchants offering the propagation materials of a species with the total number of variants of this species show a statistically significant and strong correlation for *C. moschata* ($R^2 = 0.87$, $P < 0.001$), but not for chilies ($R^2 = 0.18$, $P > 0.2$) and chayotes ($R^2 = 0.33$, $P < 0.1$).

DISCUSSION

Local Markets in the Huasteca Potosina as a Reservoir of Local Food Plant Diversity

As in other parts of Mexico, the markets of the Huasteca (**Supplementary Material 2**) offer a wide range of different products without losing their original function, which is being a platform for local farmers to sell their agricultural surplus derived from a variety of land use systems (**Figures 2**, **3**). We identified seven different food product categories offered by local merchants, consisting of healthy and diverse products. These are made accessible to the consumers and contribute to local food and dietary diversity and nutrition security (Ambikapathi et al., 2019). In this regard, it is worth mentioning that some of the recorded edible weed species are rarely found outside the local markets. These are often rich in healthy nutrients (e.g., *A. hybridus*, *Rumex crispus*) (Ranhotra et al., 1998; Akubugwo et al., 2007) but are usually not available outside the region, because they have to be consumed shortly after harvesting. Some of these edible weeds (long-shaped and round-shaped *suyo*, *Ipomoea* spp.) are culturally important but are poorly known and not consumed outside the research area. Even though it is often stated that access to and use of neglected and underutilized crops (NUS) contribute to a more secure food supply and poverty alleviation, detailed studies on their contribution to nutritional benefits and income generation are missing (Padulosi et al., 2002; Heywood, 2013). Filling these knowledge gaps is necessary to enhance policy engagement to support local markets that still provide access to a wide variety of food plants and income for small-scale farmers who produce them on their fields or recollect them from the wild environment.

Our results show that the swidden milpa is the land use system from which most edible plant products originate (43.3%), followed by home gardens (22.9%) (**Figure 4**). This is congruent with the results of a market study in central Mexico (Colin-Bahena et al., 2018). In the Huasteca Potosina, the proportion of stands run by local merchants (17.7%) who offer food plants is higher than those of non-local merchants (11.4%) (**Figure 3**). Most of their goods is self-produced, which contrasts with studies about markets in bigger municipalities and towns with more infrastructure and where the number of purchasing and reselling activities increases (Guadarrama Martínez et al., 2017; Martínez-Moreno et al., 2019). Like in other parts of Mexico (e.g., Gómez Sosa and Arellanes Cancino, 2018), the better part of the local merchant population is female (64.5%).

The high proportion of local merchant population, mainly Indigenous, who offer products from their own land use systems may also explain why almost half of the recorded plant species (48%) originated in the diversity centers and centers of domestication within the American continent, including Mexico. This is similar to the results from Whitaker and Cutler (1966), who, several decades ago, recorded a high proportion of New World plants (42%) and native plants in the market of Tehuacan, Puebla, Mexico. For the markets in the Huasteca Potosina, this trend is ongoing. However, some important food crops did not originate in Mexico but are usually considered native and form part of the local food crop diversity. Those species include, for example, bananas and mangos, also frequently cultivated by the local people and with a high intraspecific richness.

In the Huasteca Potosina, the total species and variant richness of the food products from local merchants is high, counting 275 food plant types that belong to 99 plant species. These can be subdivided into 65 species with no intraspecific diversity and 34 species with intraspecific diversity. Other market studies in Mexico recorded between 59 and 106 plant species (**Supplementary Material 2**). Differences in sampling size (number of stands) and focus group (whether including non-local merchants or not) may explain the elevated numbers of some of these studies. For example, inventories of the food plant diversity from non-local merchants would include species like apples (*Malus domestica*) or grapes (*Vitis vinifera*), which are often brought from outside the region but not offered by the local merchants in the Huasteca Potosina, who focus mainly on locally or regionally produced fruits and vegetables.

The elevated number of variants shows the importance of intraspecific richness found at the local markets and was also reported by different authors for other markets in Mexico (**Supplementary Material 2**). Culturally more important crops in the region have a higher intraspecific richness. It is worth mentioning that the total number of chayote (*S. edule*) variants is 51, which exceeds by far the number reported in other studies. For example, Juárez Hernández et al. (2014) recorded 0–13 chayote variants in seven different markets in the Oaxaca Valley, which is known for its varietal diversity of this particular food crop. In our study, the number of variants is between 0 and 35 variants per market.

Heterogeneity of Local Markets in the Huasteca Potosina

The local markets differ in stand composition and structure. On average, 87.3 plant species and variants per market were recorded, but numbers vary considerably between the markets (**Table 2**). Bigger local markets offer a higher overall richness of food plant products. Further, the number of local merchants is positively correlated to the total richness as well. This should be taken into consideration to promote the participation of local merchants, who are the main contributors to the food product diversity and prevent a homogenization of markets and a dominance of "long-distance products" from outside the region, which is linked to the loss of crop diversity (Goland and Bauer, 2004). Access to markets is a well-known problem (Almekinders et al., 2009). In the Huasteca Potosina, infrastructure is challenging, and local transportation is often expensive. For example, local transportation costs are ∼200 MXN to bring products to a market 40 km away, whereas local merchants sell an average of 509 MXN per day. Strategies to provide accessible transportation during market days are needed to make local agrobiodiversity accessible to a broader population.

Nevertheless, the role of smaller local markets should not be dismissed. They are often located in remote areas, like the markets of Tamapaxal and Tamápatz, and are important access points to fruits and vegetables for marginalized communities. The number of unique species and variants does not depend on the market size, probably because merchants in smaller markets focus on more selective products to enhance the selling probability. Further, the high number of food species and variants that are presented in <1% of the stands shows that every local merchant at each market contributes significantly to access to regional agrobiodiversity.

However, the number of different home localities of the local vendors is not positively correlated with the total richness of food plant products. The land use systems in the Huasteca Potosina are embedded in a highly heterogeneous landscape with significant differences in the crops cultivated within the same locality (Heindorf et al., 2019). This may also explain that product diversity on the marked is high, especially at the intraspecific level, even when farmers come from the same few villages. Yet, composition and abundance at the species level may be similar as shown in the case of the market in Aquismón. Here, most vendors are from the same locality and focus on species like the nopalea cactus (*N. cochenillifera*) or coriander (*C. sativum*) (**Supplementary Material 1**), but rarely offer their products in other markets, a reason why this market was clustered separately.

As shown in **Supplementary Material 1**, species proportion per market is not necessarily an indicator for its intraspecific diversity. Some specialized local merchants bring many different variants of one species and can be considered key distributors of crop genetic diversity. For example, in Ciudad Valles, <50% of the local merchants sold *S. edule*, but the intraspecific richness was considerably higher (32 variants) than in the market of Aquismon (19 variants), where more than 70% of the local merchants sold *S. edule*. Those key local merchants play a similarly important role as their counterparts in the field which refer to some very specialized farmers with a high number of variants of a particular crop (Heindorf et al., 2019).

Local Markets and Access to Plant Propagation Resources

Our results show that local markets in the Huasteca Potosina are crucial to access and use plant propagation materials, including 58 plant species. They constitute the most frequent source to obtain plant propagation resources outside the farmer's village. This evidences their important role as part of the informal seed system (Dalton et al., 2016; FAO, 2016; Kansiime and Mastenbroek, 2016). According to Kansiime and Mastenbroek (2016) and FAO (2016), local markets are especially important to access bean and maize seeds, but less important to access vegetatively propagated crops. In the Huasteca Potosina, some bean species (e.g., *P. coccineus* 36.7%, *Vigna unguiculata* 36.0%) and maize seeds (*Z. mays* (17.0%)) are also frequently obtained from local markets, next to locally relevant fruits such as *C. papaya* (30.4%) and *P. americana* (19.6%). To a lesser extent, our list includes commonly vegetatively propagated crops like *I. batatas* (4.1%) or *Manihot esculenta* (4.1%) that are partially obtained from local markets.

Farmers' preferences for local varieties are strongly linked to their favorable features in taste and adaptation to the local agro-ecological conditions (e.g., Badstue et al., 2006; Sibiya et al., 2013). These preferences are not sufficiently acknowledged in formal breeding programs and the supply of improved or certified seeds. Hence it is not surprising that commercial seed production and supply play a minor role for small-scale farmers and subsistence farmers in the Global South (e.g., Almekinders et al., 1994; Poudel et al., 2015; McGuire and Sperling, 2016; Hoogendoorn et al., 2018). Even seeds for staples from formal suppliers and that are accompanied by efforts to promote commercial seed distribution constitute only a small portion of the farmers' seed materials (Louwaars et al., 2013; Coomes et al., 2015). For farmers in the Huasteca Potosina, the provision of commercial maize seeds is irrelevant, because most of them cultivate local crop varieties (Heindorf et al., 2019). If seeds or planting materials are acquired outside their village and not from their own stock, local merchants are the main important source (92.9%), probably because goods offered by non-local merchants do not correspond to farmers' needs. At each market, we found an average of 58.4 variants of propagation materials, which underlines once more the significance of local markets to assure access to locally adapted and culturally accepted variants.

The overall food plant diversity used for propagation also includes neglected and underutilized crops (NUS). NUS are important at the local level but often lack presence in formal seed systems and are neglected in science and breeding efforts (Mabhaudhi et al., 2017). Yet, NUS have several advantages, such as better agro-ecological performance and a high nutritious value (Ebert, 2014). Their incorporation into the food system above the local level would also contribute to the diversification of a global food system that depends mainly on a handful of major food crops (the big three include rice, maize, and wheat), covering ∼90% of the daily calorie intake of the world's population (Monfreda et al., 2008). The FAO (2018a) recently recommended increasing the availability of high-quality seeds and planting materials of NUS. Besides the farmers' personal networks, local markets included in this study already provide this access to underutilized crop species like chayote and plums (*Spondias* spp.), including local variants that are not considered in the formal seed supply system in Mexico. The inventoried food plants also include species with recalcitrant seeds that are difficult to supply and cannot be conserved and stored by conventional methods such as drying or freezing. To this group belong, for example, the recorded *P. americana* and *L. chinensis*, as well as the underutilized crops that were mentioned before, like *C. papaya* and *S. edule*.

As shown by the different correlations, the number of plant propagation materials per market does not depend on market size, the origin of the merchants, or the total number of food plant richness of each market. However, as shown in **Figure 7**, each market provides a specific supply of seed and plant material in the region. We also recorded a high number of unique plant species and variants propagation materials within each market, and the rank-frequency curve (**Figure 6**) shows the same trend among all the different markets in the region. Hence, each local merchant is a valuable conveyer of local genetic resources to be passed to other local farmers who frequent these markets. Local markets facilitate open access to those resources to a broader public. In Mexico and other countries, access to local seeds is limited because they can often only be found in the local communities in remote areas. Markets are platforms outside the communities that link local producers and consumers from elsewhere, who may depend exclusively on these sources to gather locally adapted seed and plant material. Therefore, local markets should be considered an option to gather plant propagation materials for home gardens and agroecological projects in the region. Very often such projects are initiated by lifestyle migrants, i.e., people moving to places that are perceived to provide a better or different lifestyle (Santiago, 2017), who have not yet established a well-functioning seed network or seed stocks of their own.

Especially in tropical climates, seed storage is challenging, and markets can serve as backup access points when seeds are lost due to failure in storage. Likewise, they may play a vital role in disaster situations (e.g., after droughts, hail) to gather plant propagation materials when farmers' own stock is destroyed (McGuire and Sperling, 2013). During this present SARS-CoV-2 pandemic, local markets in the Huasteca Potosina were suspended or significantly reduced for several months. This may have three main market-related implications for the local people: reduced access to diversified food; shrunken income opportunities; and loss of access to seeds, as farmers who lost their seeds and cannot substitute this loss by accessing other sources within their villages will not be able to harvest in the following season. Until now, these are assumptions that should be investigated further. New insights on this topic are essential to guide political decision-making processes that respect both the immediate response to local health issues and the midterm and long-term response of the local food systems to crises. The decisions should take into account that local food production and their commerce in local markets provide income, genetic resources, and food, besides their cultural importance.

Local markets in the Huasteca Potosina are important components of the rural food system and farmer's seed network by providing income, access to a great variety of local foods, and access to seeds and plant materials for farming. They strengthen local propagation materials sovereignty and broaden the options to achieve nutrition and dietary diversity. The diversity made accessible by local merchants is high, especially at intraspecific level, and is partially correlated to other factors like market size and provenance. However, the high proportion of unique and rare food plants within and among the markets shows that food plant diversity in the local markets is not a guaranteed resource and may be threatened. To maintain and promote the use and conservation of this diversity in the future, political actions are needed, e.g., to support market access and rural infrastructure.

DATA AVAILABILITY STATEMENT

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

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. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

CH conceived of the presented idea, conducted the fieldwork, and was responsible for research design and analysis. JAR-A and AH supervised project development and verified the analysis. CH provided a draft of the first manuscript and JAR-A and AH provided critical feedback and contributed to the final version of 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.2021.597822/full#supplementary-material

REFERENCES

Adhikari, J. (2014). Seed sovereignty: analysing the debate on hybrid seeds and GMOs and bringing about sustainability in agricultural development. *For. Trees Livelihoods* 12, 33–46.

Akubugwo, I. E., Obasi, N. A., Chinyere, G. C., and Ugbogu, A. E. (2007). Nutritional and chemical value of Amaranthus hybridus L. leaves from Afikpo, Nigeria. *Afr. J. Biotechnol.* 6, 2833–2839. doi: 10.5897/AJB2007.000-2452

Almekinders, C. J. M., Cavatassi, R., Terceros, R., Pereira Romero, R., and Salazar, L. (2009). "Potato seed supply and diversity: dynamics of local markets of Cochabamba Province, Bolivia: a case study," in *Seed Trade in Rural Markets. Implications for Crop Diversity and Agricultural Development*, eds L. Lipper, C. L. Anderson, and T. J. Dalton (Earthscan, FAO: London, Rome), 75–94.

Almekinders, C. J. M., Louwaars, N. P., and de Bruijn, G. H. (1994). Local seed systems and their importance for an improved seed supply in developing countries. *Euphytica* 78, 207–216. doi: 10.1007/BF00027519

Altieri, M. A. (2002). Agroecology: the science of natural resource management for poor farmers in marginal environments. *Agr. Ecosyst. Environ*. 93, 1–24. doi: 10.1016/S0167-8809(02)00085-3

Ambikapathi, R., Gunaratna, N. S., Madzorera, I., Passarelli, S., Canavan, C. R., Noor, R. A., et al. (2019). Market food diversity mitigates the effect of environment on women's dietary diversity in the Agriculture to Nutrition (ATONU) study, Ethiopia. *Public Health Nutr*. 11:22. doi: 10.1017/S136898001900051X

Anderson, C. R., Bruil, J., Chappell, M. J., Kiss, C., and Pimbert, M. P. (2019). From transition to domains of transformation: getting to sustainable and just food systems through agroecology. *Sustainability* 11:19. doi: 10.3390/su11195272

Badstue, L. B., Bellon, M. R., Berthaud, Juárez, X., Manuel Rosas, I., Solano, A. M., and Ramírez, A. (2006). Examining the role of collective action in an informal seed system: a case study from the Central Valleys of Oaxaca, Mexico. *Hum. Ecol*. 34, 249–273. doi: 10.1007/s10745-006-9016-2

Bellon, M. R. (1996). The dynamics of crop infraspecific diversity: a conceptual framework at the farmer level. *Econ. Bot*. 50, 26–39. doi: 10.1007/BF02862110

Chable, V., Nuijten, E., Costanzo, A., Goldringer, I., Bocci, R., Oehen, B., et al. (2020). Embedding cultivated diversity in society for agro-ecological transition. *Sustainability* 12:3. doi: 10.3390/su12030784

Chappell, M. J., Wittman, H., Bacon, C. M., Ferguson, B. G., García Barrios, L., García Barrios, R., et al. (2013). Food sovereignty: an alternative paradigm for poverty reduction and biodiversity conservation in Latin America. *F1000 Res*. 2:235. doi: 10.12688/f1000research.2-235.v1

Cleveland, D. A., Soleri, D., and Smith, S. E. (1994). Do folk varieties crop varieties have a role in sustainable agriculture?. *BioScience* 11, 740–751. doi: 10.2307/1312583

Colin-Bahena, H., Monroy, R., Velázquez-Carreño, H., García-Flores, A., and Monroy-Ortiz, C. (2018). El tianguis de Coatetelco, Morelos: articulador de la conservación biocultural en el territorio. *Rev. Etnobiol.* 16, 87–97.

Coomes, O. T., McGuire, S. J., Garine, E., Caillon, S., McKey, D., Demeulenaere, E., et al. (2015). Farmer seed networks make a limited contribution to agriculture? Four common misconceptions. *Food Policy* 56, 41–50. doi: 10.1016/j.foodpol.2015.07.008

Dalton, T., Anderson, C. L., Lipper, L., and Keleman, A. (2016). "Markets and access to crop genetic resources," in *Seed Trade in Rural Markets: Implications for Crop Diversity and Agricultural Development*, eds L. Lipper, C. L. Anderson, and T. J. Dalton (Earthscan, FAO: London, Rome), 15–27.

Ebert, A. (2014). Potential of underutilized traditional vegetables and legume crops to contribute to food and nutritional security, income and more sustainable production systems. *Sustainability* 6, 319–336. doi: 10.3390/su6010319

Ericksen, P. J. (2008). Conceptualizing food systems for global environmental change research. *Glob. Environ. Change* 18, 234–245. doi: 10.1016/j.gloenvcha.2007.09.002

Evangelista, H. B. A., Thomaz, S. M., and Evangelista, L. R. (2012). Comparison of diversity indices applied to macrophyte incidence-based data. *Braz. Arch. Biol. Technol*. 55, 277–282. doi: 10.1590/S1516-89132012000200014

Fanzo, J., Hunter, D., Borelli, T., and Mattei, F. (2013). *Diversifying Food and Diets*. London: Earthscan from Routledge.

FAO (2012). *Seed System Security Assessment Report for Darfur Region*. Rome: FAO.

FAO (2016). *Seed Security Assessment: A Practitioner's Guide*. Rome: FAO.

FAO (2018a). *Scaling Up Agroecology to Achieve the Sustainable Development Goals: Proceeding of the Second FAO International Symposium.* Rome: FAO.

FAO (2018b). *Neglected and Underutilized Crops Species*. Available online at: http://www.fao.org/3/mx479en/mx479en.pdf (accessed August 02, 2020).

García López, V., Giraldo, O. F., Morales, H., Rosset, P. M., and Duarte, J. M. (2019). Seed sovereignty and agroecological scaling: two cases of seed recovery, conservation, and defense in Colombia. *Agroecol. Sustain. Food Syst*. 43:7–8. doi: 10.1080/21683565.2019.1578720

Goland, C., and Bauer, S. (2004). When the apple falls close to the tree: local food systems and the preservation of diversity. *Renew. Agric. Food Syst*. 19, 228–236. doi: 10.1079/RAFS200487

Gómez Sosa, L., and Arellanes Cancino, N. (2018). Del huerto al mercado: especies vegetales y comerciantes en la Villa de Zaachila, Oaxaca, Mexico. *Rev. Mex. Agroecosistemas*. 5, 43–54.

Guadarrama Martínez, G., Rubí Arriaga, M., Chávez Mejía, M. C., and de Jesús Sangermán Jarquín, D. M. (2017). "Conocimiento y usos de los frutos comercializados en el tianguis de Malinalco, Estado de México," in *Calificación, Valorización y Turismo. Aproximaciones al Patrimonio Agroalimentario*,eds H. Thomé-Ortiz and Á. R. Martínez Campos (Toluca: UAEM), 47–62.

Heindorf, C., Reyes-Agüero, J. A., and van 't Hooft, A. (in preparation). More than maize: inter- and intraspecific edible plant diversity in Huastec mayan landscape Mosaics in Mexico. *Econ. Bot*.

Heindorf, C., Reyes-Agüero, J. A., van 't Hooft, A., and Fortanelli-Martínez, J. (2019). Inter- and intraspecific edible plant diversity of the tének milpa fields in Mexico. *Econ. Bot*. 73, 489–504. doi: 10.1007/s12231-019-09475-y

Hernández-Rico, G. N., and Moreno-Fuentes, Á. (2010). Hongos comestibles del género Amita en el mercado de Acaxochitlán, Hidalgo, México. *Etnobiología* 8, 31–38.

Heywood, V. (2013). "Overview of agricultural biodiversity and its contribution to nutrition and health," in *Diversifiying Food and Diets: Using Agricultural Biodiversity to Improve Nutrition and Health*, eds J. Fanzo, D. Hunter, T. Borelli, and F. Mattei (London; New York, NY: Earthscan from Routledge), 35–67.

Hoogendoorn, J. C., Audet-Bélanger, G., Böber, C., Donnet, M. L., Bisani Lweya, K., Malik, R. K., et al. (2018). Maize seed systems in different agro-ecosystems; what works and what does not work for smallholder farmers. *Food Secur.* 10, 1089–1103. doi: 10.1007/s12571-018-0825-0

Juárez Hernández, L. F., Campos Ángeles, G. V., Avendaño Arrazate, C. H., Enríquez del Valle, J. R., and Villegas Aparicio, Y. (2014). Conocimiento y comercialización de chayote (Sechium edule (Jacq.) Sw.) en los mercados de Valles Centrales de Oaxaca, México. *Rev. Bras. de Agroecologia*. 9, 90–103.

Kansiime, M. K., and Mastenbroek, A. (2016). Enhancing resilience of farmer seed system to climate induced stresses: insights from a case study in West Nile region, Uganda. *J. Rural Stud*. 47, 220–230. doi: 10.1016/j.jrurstud.2016.08.004

Linares, E., and Bye, R. (2016). "Traditional markets in Mesoamerica: a mosaic of history and traditions," in *Ethnobotany of Mexico*. *Interactions of People and Plants in Mesoamerica*, eds. R. Lira, A. Casas, and J. Blancas (New York, NY: Springer), 151–177.

Louwaars, N. P., and de Boef, W. S. (2012). Integrated seed sector development in Africa: a conceptual framework for creating coherence between practices, programs, and policies. *J. Crop Improv*. 26, 39–59. doi: 10.1080/15427528.2011.611277

Louwaars, N. P., and de Boef, W. S., Edeme, J. (2013). Integrated seed sector development: a basis for seed policy and law. *J Crop Improv*. 27, 186–214. doi: 10.1080/15427528.2012.751472

Lowder, S. K., Skoet, J., and Singh, S. (2014). *What Do We Really Know About the Number and Distribution of Farms and Family Farms Worldwide? Background Paper for the State of Food and Agriculture 2014.* ESA Working Paper No. 14-02. Rome: FAO.

Mabhaudhi, T., Chimonyo, V. G. P., Chibarabada, T. P., and Modi, A. T. (2017). Developing a roadmap for improving neglected and underutilized crops: a case study of South Africa. *Front. Plant. Sci*. 8:2143. doi: 10.3389/fpls.2017.02143

Magurran, A. (1991). *Ecological Diversity and Its Measurement*. Princeton: Princeton University Press.

Martínez-Moreno, D., Alvarado-Flores, R., Mendoza-Cruz, M., and Basurto-Peña, F. (2006). Plantas medicinales de cuatro mercados del estado de Puebla. *Bol. Soc. Bot. Mex.* 79, 79–97. doi: 10.18387/polibotanica.41.10

Martínez-Moreno, D., Reyes-Matamoros, J., Rivera-Mendoza, V., and Basurto-Peña, F. (2019). Análisis de las plantas comestibles, frutas y verduras, ofertadas en el tianguis de Tepexi de Rodríguez, Puebla, México. *Polibotánica* 48, 185–203. doi: 10.18387/polibotanica.48.14

Maxwell, S., and Slater, R. (2003). Food policy old and new. *Dev. Policy Rev.* 21, 531–553. doi: 10.1111/j.1467-8659.2003.00222.x

McGuire, S., and Sperling, L. (2013). Making seed systems more resilient to stress. *Global Environ. Change* 23, 644–653. doi: 10.1016/j.gloenvcha.2013.02.001

McGuire, S., and Sperling, L. (2016). Seed systems smallholder farmers use. *Food Sec.* 8, 179–195. doi: 10.1007/s12571-015-0528-8

Meyer, R. S., DuVal, A. E., and Hensen, H. R. (2012). Patterns and processes in crop domestication: an historical review and quantitative analysis of 203 global food crops. *New Phytol.* 196, 29–48. doi: 10.1111/j.1469-8137.2012.04253.x

Monfreda, C., Ramankutty, N., and Foley, J. A. (2008). Farming the planet: 2. geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Glob. Biogeochem. Cy.* 22, 1–19. doi: 10.1029/2007GB002947

Padulosi, S., Hodgkin, T., Williams, J. T., and Haq, N. (2002). "Underutilized crops: trends, challenges and opportunities in the 21st century," in *Managing Plant Genetic Resources*, eds. J. M. M. Engels, V. Ramanatha Rao, A. H. D. Brown, M. T. Jackson (Wallingford, CAB International and Rome, IPGRI Italy), 323–338.

Pérez Castro, A. B. (2005). Los "rancheadores": porteadores de mercaderías en la Huasteca. *An. Antropol.* 39, 89–117. doi: 10.22201/iia.24486221e.2005.2.9968

Pérez Castro, A. B. (2007). Contenidos de sabor para leer la historia y vida social de la Huaxteca. *Itinerarios* 6, 81–100. Available online at: http://itinerarios.uw.edu.pl/contenidos-de-sabor-para-leer-la-historia-y-vida-social-de-la-huaxteca

Poudel, D., Staphit, B., and Shrestha, P. (2015). An analysis of social seed network and its contribution to on-farm conservation of crop genetic diversity in Nepal. *Int. J. Biodivers.* 2015:1–13. doi: 10.1155/2015/312621

Ranhotra, G. S., Gelroth, J. A., Leinen, S. D., Vi?as, M. A., and Lorenz, K. J. (1998). Nutritional profile of some edible plants from Mexico. *J. Food Compos. Anal.* 11, 298–304. doi: 10.1006/jfca.1998.0590

Santiago, C. M. (2017). Lifestyle migration and the nascent agroecological movement in the Andean Araucanía, Chile: is it promoting sustainable local development?. *Mt. Res. Dev.* 37, 406–414. doi: 10.1659/MRD-JOURNAL-D-17-00036.1

Sibiya, J., Tongoona, P., Derera, J., and Makanda, I. (2013). Farmers' desired traits and selection criteria for maize varieties and their implications for maize breeding: a case study from KwaZulu-Natal Province, South Africa. *J. Agr. Rural Dev. Trop.* 114, 39–49.

Sperling, L. (2008). *When Disaster Strikes: A Guide to Assessing Seed System Security*. Cali: CIAT.

Sperling, L., Gallagher, P., McGuire, S., March, J., and Templer, N. (2020). Informal seed traders: the backbone of seed business and African smallholder seed supply. *Sustainability* 12:7074. doi: 10.3390/su12177074

Sperling, L., and McGuire, S. (2010). Understanding and strengthening informal seed markets. *Ex. Agric.* 46, 119–136. doi: 10.1017/S0014479709991074

Van der Veen, M. (2011). *Consumption, Trade and Innovation: Exploring the Botanical Remains from the Roman and Islamic Ports at Quseir al-Qadim, Egypt*. Frankfurt: Africa Magna Verlag.

Whitaker, T. W., and Cutler, H. C. (1966). Food plants in a Mexican market. *Econ. Bot.* 20, 1–6. doi: 10.1007/BF02861922

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"The Innovation Imperative": The Struggle Over Agroecology in the International Food Policy Arena

*Colin R. Anderson and Chris Maughan**

Centre for Agroecology, Water and Resilience, Coventry University, Coventry, United Kingdom

As the gravity of the global social and ecological crises become more apparent, there is a growing recognition of the need for social transformation. In this article, we use a combination of narrative case study and discourse analysis to better understand how transformative concepts, such as agroecology, are shaped as they as they enter mainstream discursive arenas. We probe the different characteristics of the "innovation frame" and how they qualify and give meaning to agroecology. Our case study narrates the recent emergence of agroecology in the UN space and its relationship to the discursive frame of innovation. We then undertake a systematic discourse analysis of comments provided in an online consultation process on the "Agroecology and Other Innovations" report by the 2019 High-Level Panel of Experts (HLPE) in the World Committee on Food Security. We examine how different actors positioned themselves vis-a-vis the innovation frame and we analyse the discursive strategies used to advance particular political agendas. Our analysis reveals three primary sub-frames within the innovation frame (Evidence; Technology; Rights) which were deployed by both proponents and detractors of agroecology. We focus on the notion of social agency, and its different presentations, within the three sub-frames which raises a number of problematics of the innovation frame, not only for agroecology, but for sustainability transformations more widely.

Keywords: agroecology, innovation, food policy, agricultural policy, technology, critical discourse analysis, FAO (Food and Agriculture Organization)

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****Correspondence:***
Chris Maughan
chris.maughan@coventry.ac.uk

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INTRODUCTION

For at least a decade, proponents of agroecology have been hammering loudly at the gates of international policy arenas. In essence, their claim has been that agroecology has the potential to address the myriad and intertwined crises of food sustainability and social justice. Agroecology's move into the mainstream has been glacial, punctuated by numerous small victories—for example the FAO's symposia on agroecology beginning in 2014. However, the response by proponents of conventional agriculture has consistently been that agroecology is unrealistic and unviable (Bellwood-Howard and Ripoll, 2020). In an attempt to rebut these criticisms, civil society groups—mainly via the Civil Society Mechanism (CSM) of the Committee on World Food Security (CFS)—requested the production of a report on agroecology from the High Level Panel of Experts (HLPE), a respected body designed to provide independent, evidence-based analysis, and advice to the CFS. This report would, as the authors themselves described it, gather evidence and make recommendations to inform "major transformation of whole food systems" (HLPE, 2019).

While the request was eventually granted—ratified during the 44th congress of the CFS, 2017—it didn't pass without a struggle, with numerous proponents of industrial agriculture insisting that the focus of the report be broadened to include more than just "agroecology," but also "other *innovations*" for sustainability. It is this seemingly innocuous addition that is the subject of this paper. Why was the inclusion of "other innovations" so important to those routinely opposed to the transformational implications of agroecology? And what impact did it have on a report that many hoped would mark the belated entry of agroecology into the agricultural policy mainstream?

This article approaches these questions by focusing on discourse and its importance in shaping sustainability transitions. We focus on "innovation" as a discursive frame long in circulation in debates about social change and how it is being deployed in the more recent global discourse on agroecology. What kind of discursive maneuvers—or what we outline below as "framings"—are being used to influence rapidly emerging discourses of agricultural and *agroecological* innovation? Conversely, how can certain framings end up limiting "transformational" potential; that is, the ability of systems to move in the direction of justice and sustainability? To analyse the relationship between the innovation frame and agroecology, we explore the process behind the HLPE report (2019) mentioned above, in particular the public consultation which helped to shape its eventual content.

Sustainability Transitions and Discourse

While the technical and market-based dimensions of sustainability transitions have long been the focus of academic research, it is increasingly recognized that deep transformations to systems of production and reproduction are urgently needed (Scoones et al., 2015; O'Brien, 2016; Mummery and Mummery, 2019). In contrast to transition, a transformative approach centers the dynamics of governance, control and power as the key determinants of social-technical change (Stirling, 2014; Anderson et al., 2019).

Power is about more than wielding physical or material resources, it is also enacted and reproduced through discourse as words, images, and ideologies (Foucault, 1969). In regards to agroecology, the importance of discursive "disputes" or the "terrain of ideas, of theoretical constructs" is recognized as a critical factor in shaping the potential of agroecology (Fuchs and Glaab, 2011; Giraldo and Rosset, 2018, p. 546). In this case, discourse represents, "an ensemble of ideas, concepts and categories [expressed in language] through which meaning is given to social and physical phenomena, [and] which is produced and reproduced through an identifiable set of practices" (Hajer and Versteeg, 2005, p.175). However, discourse is not simply a matter of describing and representing social life, it is also closely related to power as it is socially constructed, shaping behavior, language, and thought of those who participate in it.

When discourses "enter and achieve salience or dominance in particular social fields or domains," they inform new ways of acting, identifying and organizing (Fairclough, 2013, p.77, 358). Discourse thus plays an important role in providing legitimacy for some transition pathways, while delegitimizing, deemphasizing or re-casting others (Fuchs and Glaab, 2011; Geels et al., 2014; Montenegro de Wit and Iles, 2016). A particularly striking example of this can be seen in the prominent positioning of "feed the world" narratives in legitimizing expansions to existing industrialized production, and *de*-legitimizing ecologically productive, but lower-yielding production (Fouilleux et al., 2017; Anderson et al., 2020a). Through their discursive power, actors influence the perceptions and normative assumptions of definitions that are deployed in political arenas, which shapes the resulting policies, actions, norms, and procedures (Hajer and Versteeg, 2005). Our approach here offers insight not only on a highly contested discourse of agroecology—and in particular its development within a mainstream or hegemonic discursive arena—but more broadly in the ways in which such counter-hegemonic language in sustainability transitions is itself countered, reframed, and neutralized.

Framing Agroecology and Innovation

Agroecology has been routinely framed by its proponents as an alternative paradigm to the industrial food and agricultural regime (Nyeleni, 2015; Rosset and Altieri, 2017; Anderson et al., 2019; González de Molina et al., 2019). Yet, agroecology does not have a single fixed meaning and it has been argued there are multiple "agroecologies" (Méndez et al., 2013) as it is re-signified (Rivera-Ferre, 2018) and co-produced (Loconto and Fouilleux, 2019) by different actors with different values, intentions and worldviews (van Hulst et al., 2020). Indeed, agroecology, to some, is an ambitious and integrative set of principles intended to govern systems-level sustainability transitions. To others, agroecology is being cast as a small (minor) subset of production practices alongside many other options. Yet still to others, agroecology has been described as an outdated, impractical and even dangerous approach because it undermines the centrality of yield and profit as the object of agricultural development (Tom, 2020).

The recent global attention to agroecology in academia, policy-making, and amongst practitioners and social movements has simultaneously generated excitement and anxiety amongst proponents of a transformative agroecology. On the one hand, many view the institutional uptake of agroecology and its mainstreaming as a vital part of the transition to sustainable food systems. On the other, history has demonstrated how once radical and transformative frameworks for agriculture have become deformed and denuded of their transformative potential as they become adopted and incorporated into existing markets, policy-frameworks, and as powerful actors step in to discursively and materially control the dynamic (Levidow et al., 2014; Laforge et al., 2016; Giraldo and McCune, 2019; Anderson et al., 2020b). For example, the involvement and incorporation of organic agriculture into corporate-led chains has been derided for undermining the values and the transformative potential that the pioneering organic movement was founded on (Guthman, 2004).

In this article, we engage with the complexities and problematics of institutionalizing transformative concepts like agroecology, focusing particularly on what we refer to as the "innovation frame" and how it is being mobilized by different actors in relation to agroecology. Innovation has been used over time as a way of thinking about societal change, and in regard to sustainability and agriculture more specifically (El Bilali, 2019). The term was first popularized by Joseph Schumpeter, who defined it as, "doing things differently" (Schumpeter, 2005 [1939], p. 84); indeed, this simple framing might explain how innovation has become a ubiquitous concept in mainstream development models. However, whilst the term remains at the center of debates today about how society changes, it has continued to signal predominantly market-led and technological pathways for social change. As Pansera and Owen (2018: p.xxi) suggest, innovation "has the potential [to develop] a hegemonic framing that emphasizes features typical of neoliberal agendas such as competitiveness, ownership, productivity, efficiency, and market-orientation." Indeed, leading economic thinkers have even begun to frame it in terms of the "innovation *imperative*" (OECD, 2015), elevating the fetish for novelty and technological "progress" into an existential ultimatum familiar in developmental discourse: modernize or disappear.

In the EU, the "Innovation Principle"—though slightly less insistent than the OECD's innovation "imperative" formulation (OECD, 2015)—has been criticized for its use in circumventing environmental and health safeguards in favor of market-ready innovations (Anderson, 2020). A growing number of voices, including those adopting post-development, feminist and critical agrarian studies perspectives (Kothari et al., 2019) have worked to unveil the colonial nature of the modernist assumptions of change that underpin terms like innovation. From these perspectives, innovation has been used to advance a linear conceptualization of change (toward a singular modernity), where things that are innovative are only valued as such when they pull in the same direction as technological "progress" and wealth accumulation.

In agriculture, the innovation, the innovation frame has been criticized for its preoccupation with increasing productivity, profits, and economic growth (Quist et al., 2013). An emergent literature has begun to examine the effects of a new generation of agricultural technology, sometimes referred to as "4th industrial revolution (4IR)" technologies, suggesting their claims to social and ecological benefits may be unsubstantiated (Miles, 2019), that their negative impacts are downplayed (Barrett and Rose, 2021), and may ultimately be incompatible with agroecological principles, especially the "undesirable side effects [..] of digital technologies [on] rural employment and rural-urban migration" (Klerkx and Rose, 2020).

Despite the intimate link between these technologies and the innovation frame, the general response of these authors has been to call for a re-purposing of innovation, toward more "responsible" and "inclusive" innovation systems. In doing so, they follow a number of scholars and activists from different backgrounds calling for a similar re-framing of innovation to mobilize it as a tool for pursuing the social, ecological and economic dimensions of sustainability transitions. There have been calls for a normative basis to direct what type of innovation should be promoted to foster transition toward sustainable food systems (El Bilali, 2018) and explorations of the potential of inclusive innovation (Levidow and Papaioannou, 2018), grassroots innovation (Seyfang and Smith, 2007), social innovation (Baker and Mehmood, 2015; Rover et al., 2016), retro innovation (Stuiver, 2006), coupled innovation (Meynard et al., 2017) and agroecological innovations (Uphoff, 2013; Berthet et al., 2015). In the field of agroecology, many have engaged with these traditions to modify or qualify innovation in some way to prioritize the agency of marginalized groups, to assert the importance of incorporating environmental and social aspects as a key goal of innovation and more generally to be much more inclusive of the wider range of activities that drive change in food systems (Rover et al., 2016; López-García et al., 2018; El Bilali, 2019; Schiller et al., 2019; Marchetti et al., 2020).

Despite this growing literature, innovation is very seldom historicised within the genealogy of capitalism, and can easily be repurposed unwittingly or disingenuously to contest capitalism itself. In an attempt to redress this, our article examines the discursive maneuvers of differently positioned actors in relation to innovation and agroecology, while bearing in mind this political-historic genealogy of innovation. Our article presents a discursive analysis to understand what the innovation framing "does" in debates on the governance of food and agriculture, and particularly for radical proposals for transformation such as agroecology. Can innovation be recast, as some have hoped, to bring it in line with the principles of agroecology? Or will innovation continue to foreground productivism and accumulation ahead of urgent social and environmental concerns?

METHODOLOGY

This study focuses on a particular discursive arena—The debates on agroecology and innovation in the United Nations. A discursive arena is an analytic boundary deployed in processes of deliberation and negotiation. It involves demarcating an arena and a process within which different views are performed, so that meaning, and understanding can be harvested for the purposes of analysis. In forums for public participation, for example, this analysis is often directly linked to policy-making processes. Indeed, high level policy documents have provided the focus of numerous studies of food and agricultural policy (Barrett and Rose, 2021; Lajoie-O'Malley et al., 2020; Maughan et al., 2020). In contrast, this study focusses on the deliberation of differently positioned actors within the discursive arena, rather than the policy outcomes themselves. The construction of discursive arenas is a political process where decisions on which views are included, and which perspectives and knowledge are harvested and prioritized, are made by those able to wield or gain power within the domain. Our approach is intended as a way to make legible the disparate and contrasting forces convened within policy-making processes.

The UN space is important because of its role in advising governments, directing resources, and the high visibility of UN debates and programs on the world scene. For these same reasons, the FAO is also a contested space where many actors jostle to shape the food and farming discourse. In order to contextualize, and to interrogate the innovation frame within this discursive arena, our study weaves together a combination of case study and critical discourse analysis. The narrative case study helps us first to understand how the particular discursive arena has been constructed and what the political dynamics behind its construction have been. We have already explained above in the introduction how the process of selecting the title for the HLPE report was marked by a conflict over the inclusion of the word "innovation." The frame analysis of the comments from the public consultation on this report, which we embed within this narrative case study of agroecology in the UN, offers a snap-shot of the different and contesting voices often hidden in published policy documents. Mapping the dynamics of this contestation, we argue, will be vital for understanding the broader struggle to determine what innovation is for and whose interests it serves.

Participant Observation and Narrative Case Study

The first part of our analysis (presented in the first and final section of our results) reviews and analyzes the progression of agroecology in the U.N. system over the last decade—particularly the FAO and the HLPE of the CFS, culminating in a recent report on "agroecology and other innovations" (which is the focus of the second section of our results). The FAO is an international intergovernmental institution, funded and governed by nation-states and provides basic research, information gathering and dissemination, formulation of policy recommendations, technical assistance, and government consultation. The goals of FAO are to: "Help eliminate hunger, food insecurity, and malnutrition; Make agriculture, forestry, and fisheries more productive and sustainable; Reduce rural poverty; Enable inclusive and efficient agricultural and food systems; Increase the resilience of livelihoods to threats and crises; Establish technical quality, statistics, and cross-cutting themes" (FAO, 2020). It is a highly influential forum where discursive processes are highly visible, and translated into budgetary outcomes in FAO and indirectly in its influence on national policy-making.

In order to construct this narrative account, we draw from participant observations in the process, analysis of related UN literature, web-analysis, and a small number of interviews with key informants involved in the UN process. This narrative case study helps not only to contextualize the discursive dynamics at play in the UN policy arena (especially the types of actors and their different positionalities), but also to connect it to external events and trends. To this end, after the frame analysis we return to the narrative account in the following section, offering a brief examination of the final report as well as a number of other salient policy events. A full analysis of the final report was beyond the scope of this article, as it was our intention to prioritize not the policy publications (which get a lot of attention) but the often-hidden, largely implicit and typically highly divergent positions taken up by participants during the policy consultation and formulation processes.

Critical Discourse Analysis of HLPE Report on Agroecology and Other Innovations

The second component of our analysis (presented in the second section of our results) uses critical discourse analysis of 141 comments provided as a part of the official online consultation for the HLPE report "Agroecology and Other Innovations" (HLPE, 2019). The High-Level Panel of Experts for Food Security and Nutrition (HLPE) acts as the science–policy interface of the UN Committee on World Food Security (CFS). The CFS is the foremost inclusive and evidence-based international and intergovernmental platform for food security and nutrition (FSN). The HLPE produces scientific, policy-oriented reports, including analysis and recommendations, serving as a comprehensive and evidence-based starting point for policy debates at the CFS. The HLPE draws together existing research and knowledge to produce global, multi-sectoral, and multi-disciplinary analysis in high profile reports. HLPE studies combine scientific knowledge with experiences from the ground, through its consultative process. The topics and scope of the CFS are determined by the HLPE steering committee that start with a political question and request formulated by the CFS. The 14th report, on "Agroecological Approaches and Other Innovations" (HLPE, 2019), is the focus of this article.

The HLPE runs two open consultations per report: first, on the scope of the study; second, on a V0 "work-in-progress" draft. Consultations enable the HLPE to better understand the issues and concerns, and to enrich the knowledge base, including social knowledge, thriving for the integration of diverse scientific perspectives and points of view. Our analysis focuses on the publicly available comments that were submitted as a part of this second consultation. The HLPE committee incorporates the input from these consultations into a final draft which is subjected to external scientific peer-review. HLPE reports are then published and form the basis of policy discussions and debates in the CFS.

In response to the online consultation on the zero draft of the HLPE report on Agroecological Approaches and Other Innovations, 141 comments were submitted. These comments were provided—in many cases collaboratively—by representatives from 37 different countries. According to the HLPE's own synthesis of the report (HLPE, 2018), "7 contributions come from national governments, 32 from civil society and NGOs, 23 from the private sector, and 57 from academic or research institutes." Despite this institutional spread, there was a clear regional bias with 50 percent of the contributions come from Europe, 21 percent from North America, and only 12 percent from Latin America and the Caribbean, 8 percent from Asia, and 6 percent from Africa. The remaining 2 percent from the Near East and South-West Pacific. Overall, 26 percent of the contributions come from "developing countries."

Critical discourse analysis refers to a broad church of approaches to analyzing language which address its involvement in the production and reproduction of power (Fairclough, 2013). Methodologically, CDA is intended to interrogate discursive practices to understand how they reproduce and extend particular social and political relations by "normalizing" certain assumptions and delegitimizing others. Our study investigated these discursive strategies and interactions by differently positioned of actors around the role of agroecology as a framework for sustainability transitions in food systems.

In order to help make sense of the different ways that agroecology is being constructed, we employ the concept of framing. Frame analysis is an approach to discourse analysis used to understand how discourses are constructed to support particular ideological positions or worldviews (Steinberg, 1998). A frame is an interpretation that simplifies and condenses "the world out there" (Snow and Benford, 1992, p.137) and offers a way of understanding and projecting a particular position or concept. Thus, in any discursive arena where actors are debating or invoking agroecology, multiple frames are advanced by actors from different positions of power through an often-implicit political process of contestation. The discursive arena is thus co-constructed between different actors with differential power vying to frame and shape discourse (in our case about sustainability transitions) to promote justifications, prognoses, policies, and courses of action that align with their own interests. Frame analysis provides an approach that can make sense of these (often implicit) discursive dynamics, framing processes, and power relations.

We used n NVivo Qualitative Data Analysis software (V12) to code the 141 official comments in the HLPE process on the zero draft. All submissions were spot-checked and any that offered only minor or insubstantial inputs (e.g., tweaks in wording), that were duplicate entries or those that copied and pasted generic text (e.g., previous publications) were eliminated. The remaining 102 responses were coded to identify emergent themes. The two authors each open coded the documents, generating analytical memos focusing particularly on data that reflected the relationship between agroecology and innovation. The coding, content and analytical memos were then reconciled through dialogue between the researchers. As a part of this iterative process, the larger set of initial open-ended codes were iteratively combined and hierarchized into three main subframes. These sub-frames were constructed to understand the contested views on innovation as they relate to agroecology, and to better understand how each sub-frame is normalized and rationalized by actors. The contours of the three main sub-frames (**Table 1**) are articulated in Part B, below, presenting their main dimensions illustrated with emblematic quotes.

TABLE 1 | Original codes and how they were grouped under final three "sub-frames."

Supportive of innovation	Sub-frame	Critical of conventional notions of innovation
• Conventional and standardized metrics should be used to assess the effectiveness of innovations • Non-scientific knowledge is less reliable • Economic productivity and yield should be prioritized	Evidence	• New and more holistic measures of ecological and social impact should be developed • Agroecology is only full known when incorporating diverse ways of knowing and thus measuring • Knowledge needs to be evaluated *in situ* • Simultaneously prioritizes ecological, economic and social productivity
• Novel technology is the primary driver of social change • Novel technologies will likely benefit farmers • Novel technologies are preferred by youth • Novel technologies can "feed the world"	Technology	• Industrial/novel technologies can create many negative outcomes • Social innovations are as important as technological ones • Innovations should be developed at all levels, especially *in situ* • Farmers and citizens are innovators (i.e., knowledge producers)
• Farmers should have the right to choose from the full range of agricultural products and innovations • Intellectual property rights of technology developers should be prioritized	Rights	• Human rights should be the overarching framework to evaluate "innovations" and protect the agency of people in all spheres of life • Rights of the "most affected" should be prioritized • Uphold the "precautionary principle"

RESULTS AND DISCUSSION

Part A: Case Study: The Progression of Agroecology and Innovation in FAO and the HLPE

While elements and practices of agroecology had been present in the FAO for many years, it was since ∼2010 when civil society, in concert with a handful of supportive governments, began to push for agroecology in FAO in a substantial way. From 2015 to 2019, the FAO engaged in a Global Dialogue to examine the potential role of agroecology as a pillar of agricultural development (Loconto and Fouilleux, 2019). At the same time, support for agroecology was growing and being advocated for by some member states (the "Friends of Agroecology"). However, these efforts to elevate agroecology in FAO were opposed by some member states (Canada, Australia, Argentina, and especially the USA) who felt agroecology did not promote their own national interests or the vision of agricultural development they project into the world. Despite this opposition, the International Year of Family Farming in 2014 created a political opportunity for FAO to bolster the theme of agroecology (Loconto and Fouilleux, 2019).

The proposal was to hold a symposium on agroecology followed by a series of regional seminars. However, the approval was conditional with the USA insisting that:

1. The symposium had to be a technical symposium meaning it would have no formal political weight in FAO.
2. Speakers were also told they could not include certain words in the official program: international trade policies, genetically modified organisms (GMOs), or even the use of the term "food sovereignty," which were viewed as too political and threatening (Giraldo and Rosset, 2018).
3. Whatever was organized for agroecology, a parallel process had to be organized for biotechnology (Source: interview).

Thus, FAO set forth to organize a two-stream process. An initial international symposium was organized in Rome for both agroecology (2014) and biotechnology (2016) resulting in final reports for each (FAO, 2016). Follow-up regional consultations were planned in both streams.

TABLE 2 | Timeline of key FAO moments regarding agroecology and innovation. Source: interviews, FAO (2018).

	Agroecology	Biotechnology
	(2013–2016) Civil society contests biotech. Agroecology beginning to gain ground in FAO	
Kick off symposium	1st International Symposium on Agroecology (September 2014)	1st International Symposium on the Role of Agricultural Biotechnologies in Sustainable Food Systems and Nutrition (February 2016)
Regional multi-stakeholder meetings	7 on Agroecology in: Brasilia (June 2015), Dakar (November 2015), Bangkok (November 2015); La Paz (September 2016), Kunming (August 2016), Budapest (November 2016); Tunis, (November 2017)	2 on Biotechnology in: • Asia & Pacific (September 2017) • Sub-saharan Africa (November 2017)
Closing Symposium	2nd International Symposium on Agroecology (April 2018)	N/A
Innovation symposium	International Symposium on Innovation for Family Farming (November 2018)	
HLPE Report in CFS	(2018–2019) HLPE Report on Agroecology and Other Innovations	

Seven agroecology regional consultations were then scheduled between June 2015 and August 2016 in all regions (**Table 2**) with the exception of North America, culminating in a final report that synthesized all of the debates across the meetings (FAO, 2018). Despite plans for a similar number of regional meetings on biotechnology, only two were ultimately organized. At the first regional meeting held in September 2017 in Asia/Pacific, social movements participated and used the forum to "ask inconvenient questions" (source: interview) and to raise criticisms of biotechnology in the public. Evidently concerned by these developments, the FAO biotech process and the remainder of the regional conferences were canceled (Source: Interview).

In 2018, a second international forum was held in Rome on agroecology as the culmination of the Global Dialogue on Agroecology where over 900 people attended and participated in the launch of FAO's "scaling up initiative." The chair's summary, read at the end of the meeting, contained an emphasis on "transformation" and the rights and agency of food producers. But the summary was later censored and cut back (Loconto and Fouilleux, 2019). Meanwhile, proponents of biotech within FAO regrouped and started a process focusing instead on "innovation," organizing an international "Agricultural Innovation for Family Farmers" in November 2018 (source: Interview). In this context, agroecology was discussed, alongside other emerging technologies, including big data analytics, automation, and GMOs.

This brings us to the episode with which we opened this article: the parallel process, pushed by civil society in the World Committee on Food Security, to initiate a High Level Panel of Experts (HLPE) report on Agroecology. While proponents of agroecology had long-advocated for an HLPE report that focused on agroecology, this was again obstructed by proponents of industrial agriculture (source: interview). Eventually, with enough pressure, an HLPE report on agroecology was confirmed, but with the concession that the report couldn't only be about agroecology, but rather about Agroecology and "*Other Innovations.*"

Thus, both in this HLPE report, and through the mutation of the biotechnology process into an innovation process in FAO, innovation functions as a frame to bring agroecology and contrasting (and arguably antithetical) approaches such as biotechnology into a common frame. This innovation "framing" is thus the focus of the next section where we report on our analysis of three innovation sub-frames we identified within the HPLE consultation process.

Part B: Frame Analysis of HLPE Consultation Process

The Evidence Sub-frame: Innovation as Valid Through Measurement

Decisions about how and what we measure shape material realities. Like frames, they simplify and condense information, foregrounding particular dimensions as indicators of success and failure, and ignoring or downplaying others. Accordingly, there was a strong focus on measuring and evidencing the impacts of innovation across the comments. Given HLPE's stated aim, to provide "a comprehensive overview of the [...] best available scientific evidence" (HLPE, 2019), this emphasis on evidence is not a surprise. While an appeal to evidence is often presented as a way to objectively value and compare different innovations, a closer review of the comments demonstrates that its use can also limit the horizon of what is considered "legitimate" when using the dominant methods and tools of documenting evidence.

The respondents who were more skeptical of agroecology often pointed out a shortfall in acceptable evidence, claiming, *"the innovations as described are underrepresented in an essential area, measurement" [Donald Moore, Global Dairy Platform]*. Others appeared to endorse the value of alternative measures of evidence such as for well-being, only to reject them in favor of established economic metrics:

> *While the well-being perception of local communities is an important subjective indication of sustainability, objective economic factors, including household income and variability, more clearly demonstrate contributions to the sustainability of communities and the agricultural system. [Kristen Hendricks, USDA]*

In doing so, this commentator drew from familiar arguments about the relative immeasurability of social, cultural, political and many ecological outcomes, in contrast to those that measure economic outcomes and yield. The same respondent complained that, *"It is not clear where the draft report stops being scientific and starts being political" [Kristen Hendricks, USDA]*, disparaging the impacts of innovation that cannot be "objectively" measured. At times, the same respondent demonstrated a clear distaste for the draft document, and the "description of agroecology" contained within it, suggesting that it was "aspirational, idyllic, utopian, and not based on reality" (Ibid.). Whatever the legitimacy of the respondents' concerns about evidence gaps, the dismissive language is noteworthy. This discursive maneuver disingenuously nods to the importance of social outcomes, such as well-being, but excludes the social and political from formal consideration (and evidencing) because they are immeasurable by conventional standards.

Elsewhere, more subtle discursive maneuvers were at play that—when read carefully —revealed the prioritization given to the profitability of agricultural innovations. One particularly interesting example stated, *"With appropriate consideration given to potential consequences and trade-offs, responsible research should be the foundation of practices recognized as genuinely innovative." [Brian Baldwin, IAFN]*

On the surface, the comment appears to be sympathetic to an integrative approach to measuring innovation, positioning "responsible research" as the "foundation" of what is "genuinely innovative"—yet the claim is subtly caveated. The organizing principle here is in fact the "*appropriate consideration* given to potential consequences and trade-offs" [emphasis added]. If read in terms of earlier stated interests of "objective economic factors," this must be seen as synonymous with the profit motive of the agricultural private sector, rather than, for example, long-term environmental impacts or human rights infringements. As such, this is an example of neoliberal double-speak—cementing the primacy of the market in the delivery of social goods while appearing to defer to responsible research.

A similarly subtle sleight of hand is visible again when the same respondent writes: *"We encourage the HLPE to broaden the thinking on innovation from the current draft which demonstrates an extremely narrow focus placed solely on social process of innovation." [Brian Baldwin, IAFN].* While disagreements routinely orbit around questions of salience like this—one person's broadening of focus, is another's narrowing—such statements bring to the fore the predominance of market logic in shaping our understanding of what innovation is for. While critics of agroecology sometimes argued for the breadth and depth of conventional measures, this was often in contradiction with their recommendations. Take, for example, discussion around farmer livelihoods. Conventionally this is measured in narrow market terms like GDP or household income, in a way that can side-line measures of other important factors such as mental health and ecological resilience. It was clear that for some respondents this is the way that it should stay. One respondent, for example, argued that, *"Simply put, it is critical to recognize that farmers throughout the world are business owners"*, downplaying their roles as ecological stewards, community members, and knowledge producers. "*Simply put*" is indeed telling here, as such a framing forecloses a consideration of farmers as anything other than passive participants in economic exchange, who, as the same respondent put it, *"need to be provided with all of the means, in terms of both information and physical tools, that could support their objectives" [Donald Moore, Global Dairy Platform]*. This framing is crucial, appearing on the surface to be about farmer agency (i.e., by supporting "their objectives") while on the other had constructing their role as recipients of innovation. Here, farmers are provided with "all of the means" but are excluded from the innovation process, thereby limiting their political and practical horizons.

By contrast, some respondents were keen to point out that conventional economic measures were only one concern among many, and called for greater, *"reflection on the role indicators play in the design and implementation of policies" [Katia Roesch, Coordination Sud]*. Advocates of social innovation, for example, could be characterized by their attempt to reorient—even "widen"—innovation processes to include social needs rather than solely market outcomes. This was reflected in calls to move, *"toward holistic agroecological indicators such as nutritional value, ecosystem biodiversity and services, climate change resilience, and farmer innovation." [Fabio Leippert, Biovision]*.

While proponents of agroecology often acknowledged shortcomings in the agroecology evidence base, this was often presented as a frontier to be overcome rather than a fatal flaw as, *"[one] of the missing pieces is the inadequate level of research to assess the impact of AE on women's economic and social empowerment." [Tontie Binado, ActionAid].* In a similar vein, another respondent claimed that, *"More nuanced and in-depth exploration is needed to elucidate how knowledge is linked to and permeates agroecological practice; and the unique ways in which agroecology spreads and scales out knowledge and innovation." [Faris Ahmed, USC Canada].*

While agroecology is hardly a new field of study, its calls for a "fundamental shift" in the way our food systems are measured (IAASTD, 2009) have long been hamstrung by a significant underinvestment in agroecological research e.g., (Pimbert and Moeller, 2018; Moeller and Devlaux, 2020). As one respondent illustrates, such *"paucity of data [creates] a bias [toward] the economic benefits of industrial agriculture [. . .] The data paints a biased picture and does not take into account local results in terms of food security." [Katia Roesch, Coordination Sud]*. Accordingly, many respondents to the consultation clearly conceived of agroecology as an ongoing project with evidence still to be gathered and emphasized the need for *new measures* capable of capturing the multiple benefits arising from agroecological systems.

In contrast to respondents who used the innovation frame to validate generalizable science and standardized indicators were those pointing out the importance of local and indigenous knowledge. Such perspectives raise important questions about the epistemological compatibility such perspectives with an indicator- and science- led approaches to innovation. As one respondent argued,

> *Local and traditional knowledge is often not documented in peer-reviewed studies, and much richness and local experience salient to these issues is lost. We suggest that a greater proportion of case studies and research from civil society organisations is included to balance the scientific "way of knowing" especially since agroecology seeks to foreground the local and traditional knowledges of food producers and consumers. [Vanessa Black, Biowatch].*

As this respondent suggested, the appeal to standardized indicators as the measure of quality and worth can easily erase local, traditional, and farmer knowledge and the benefits that agroecological approaches have in ways that are highly specific to place. Advocates of agroecology have historically resisted such generalized approaches, citing the links between processes of universalisation and standardization and efforts to advance imperialist modes of "development," and such views were strongly represented in the consultation.

The Technology Sub-frame: Innovation as Technology

The second major sub-frame concerns "innovation *as* technology," in particular the dominant conception of technology as novel techniques, methods and tools, often packaged as machines or technologies deployed at the farm level. From the labor-saving technologies of the industrial revolution, to the use of robotics and genetic modification in contemporary systems, agricultural technologies have consistently stirred controversy. Have such technologies made life easier for farmers, eaters, and society as a whole? have they generated more and complex problems in the long-term? The innovation discourse has largely emerged alongside such controversies, being often seen as synonymous with "top down," or "externally introduced technologies" (Joly, 2018). Despite efforts to develop broader conceptualisations of innovation that incorporate social processes, politics and other conceptual features, there remains a strong tendency to reduce innovation to uptake of novel technologies.

Unsurprisingly, the HLPE consultation surfaced familiar tensions in its consultation, with respondents positioning themselves differently in relation to technology by either—(a) endorsing the existing repertoire of industrial agricultural technology as a key driver in beneficial changes in the agricultural sector, or (b) problematising top-down approaches to innovation as technology, either with reference to the destructiveness of existing technologies, or by calling for a broader conception of what innovation and innovative technology is and the benefits it should produce.

A prominent feature of the innovation as technology frame were claims that existing technologies were being unfairly criticized. As one respondent puts it, "*ISF regrets the negative tone that this paragraph takes on the technology and innovation that has so greatly benefited food security and nutrition in developed countries during the past decades" [Helene Guillot, ISF].* Here and elsewhere, pro-technology respondents argued as if controversies around certain technologies had already been settled. As another respondent put it, *"The UN has already [...] formally supported the need for convergence of all the available technologies and their use in integrated solutions that are able to address local needs and societal requirements". [Brian Baldwin, IAFN].* Here, technologies are framed as indispensable tools for meeting "needs," though needs which are apparently defined from above, which pacify participants (by offering "food security" rather than meaningful involvement in decision-making), and which are vaguely defined ("societal requirements"). By contrast, any consideration of these technologies' long-term impacts, or of affected communities' collective rights to technology sovereignty are omitted.

As with the previous sub-frame, critics of agroecology sometimes pointed to the emotional and unreliable nature of oppositions to technology driven approach. As one respondent put it, the draft, *"fails to consider unjust fears of technology and emotion-driven policy-making that is not based on science" [Brian Baldwin, IAFN].* In doing so, the respondent surfaced a long-running conflict between "precautionary" vs. "risk-based" approaches to technology development. Generally speaking, this debate revolves around how to deal with the lack of knowledge about the impact of technological or procedural change. Whereas the precautionary principle states that the "the proponent of an activity, rather than the public, should bear the burden of proof" (Brand, 2010), a risk-based approach contends that evidence for hazards be established *before* restrictions are imposed (Garnett et al., 2018). While "risk" might reasonably be seen as synonymous with (rather than opposed to) "precaution," its use by organizations like the "European Risk Forum" (ERF) has illustrated its capacity to undermine the precautionary principle. The ERF's support of the "innovation principle," for example, has been seen by some as a way to push through controversial innovations (Anderson, 2020), prioritizing the "needs" of the sector to bring new technologies to market, over those of the long-term risks of those technologies to human and planetary health.

While some respondents called for a commitment to, *"the Precautionary Principle"* as the only way to, "*assess the consequences of innovation" [Sarah Schneider, MISEOR],* "precaution" and "risk" also illustrate the confusing ways such debates play out in the innovation discursive arena. In this case, "risk" is deployed in an apparently misleading way to cover the less palatable interests of the private sector. Similar examples appear elsewhere, to such an extent that an increasingly shared discursive territory emerges, with key words and phrases bridging, hybridizing, and borrowing across the technophilic-technocritic spectrum. For instance, as one contributor suggests,

> *New plant varieties created through methods of biotechnology and novel breeding techniques have the opportunity to provide growers with varieties that are adapted to their local conditions and resilient to a changing climate. [Brian Baldwin, IAFN]*

Rather than emphasizing productivity gains, this respondent draws on the urgency of climate change and local conditions—more readily associated with the agroecology and food sovereignty movements—to justify controversial and unpredictable proprietary technologies. This discursive overlapping repeats a familiar pattern of capture by the agricultural mainstream, aimed at absorbing the challenges which come from those advocating more radical transfers of power.

Another key area of shared language could be seen in the appeal to a number of marginalized stakeholders often associated with agroecology, such as women, smallholder farmers, and especially youth. Referring to the latter, respondents noted technology's role in attracting and empowering such groups to view agriculture as a legitimate option for their futures. Such an empowering process could not exist, so one respondent claimed, if innovation were to be seen as *"largely limited to the adoption of historical practices" [Donald Moore, Global Dairy Platform]*. Another respondent highlighted the role of "external inputs," claiming that they,

> could mean relief from backbreaking labor, particularly for the poor, women and children on whom this task often falls based on "local knowledge and traditional". From a social just [sic] perspective this needs to be recognized. [Gloria Jaconelli, CropLife International].

Again, not only do we see the invocation of marginalized groups to justify externally introduced technology, but the simultaneous attempt to discredit "local" and "traditional" technologies and knowledges. Agroecology—in its affirmation of traditional technologies, local knowledge, and its aim to gain autonomy from expensive proprietary technologies and external inputs—is characterized not only as inefficient or outdated, but also "socially *[un]just*." In line with the idea of the "innovation imperative," top-down technological extension is advanced here not only as a rational choice, but as a *moral imperative*: to refuse such technologies is to abandon the poor and marginalized to destitution and even death. This caricature of agroecology as wholly anti-technology, when combined with this moral imperative, is a powerful though unrepresentative claim against agroecology and its proponents. As described in the following paragraphs, proponents of agroecology generally advocate for appropriate technology and science in agroecological systems, and for the importance of civil society governance in weighing the impacts, advantages and disadvantages of technology in the long term social, economic and ecological wellbeing of rural and urban people.

As one might expect, there were also many respondents who were critical of a technology-led approach, pointing to the long-term risks that certain technologies pose to food producers and society. Genetic modification was frequently cited and identified as problematic, with one respondent calling for the, *"HLPE not to use this subject to advance GMOs [...], new and under-researched gene editing technologies, [...] CRISPR and allied technologies', concluding that 'this is not what "innovation" is." [Rahul Goswami, Center for Environmental Education, Himilayas]*. Other respondents pointed to the toxic and unknown impacts of GMOs, arguing that nature should not be privatized but to rather treat, *"seeds and biodiversity as a commons that cannot be enclosed by any form of IPRs." [Laura Gutierrez Escobar, Grupo Semillas, Colombia]*. These perspectives further contested the idea that such technologies were not only legitimate alternatives to agroecological innovations, but compatible with them. After dissecting biofortified food and GMO to reveal the risks and drawbacks of these approaches, one respondent suggested that

> *the title of the report to be modified, since it leads to the understanding that "other innovations for sustainable agriculture and food systems that enhance food security and nutrition" have agroecological character, which is not the case. [Carolina Alzate Gouzy, Núleo de Agroecologia e Produção Orgânica UnB, Brazil]*

Such contestations reflected the subtle way in which the innovation frame offers a "menu of options" which are all vaguely presented as viable and desirable, and therefore difficult to refuse (Van Dyck et al., 2019). Some participants were well aware of the implications of such a framing, arguing that innovation in agricultural technologies is far from an exclusively modern or industrial phenomenon; on the contrary, agroecological innovations could be seen as historically integral to place-specific co-evolution of social and ecological systems. As one commentator put it,

> *It should be acknowledged that agricultural innovation has been taking place for thousands of years...and has continuously adapted to changing social and ecological developments....This evolving relationship of coproduction underpins agroecology and differentiates it from "other innovations." [Anisah Madden, AFSA]*

While clearly problematising the simplistic relation between technology and beneficial social and environmental outcomes, such respondents were not necessarily "anti-technology." Indeed, this same respondent acknowledged *"the use of digital technologies to reduce Food Loss and waste is a positive application*", before reminding us that *"this is not the only application of big data and digitalisation of the food chain' and calling for 'more critical investigation and analysis." [Anisah Madden, AFSA]*. In short, those critical of technology, could consistently be seen to call for a revised understanding of technology and innovation, one which began by "decoupling" technology from the "concept of innovation" and recoupling it to a series of other social and environmental issues, such as *"the right to adequate food and the pursuit of food security and nutrition." [Stefano Prato, CSM]*. At the heart of these claims, as we will explore in the next section, is a call for a re-integration of the innovation processes—arguably so long a feature of agricultural development—back into the lives of those most affected by them.

The Rights Sub-frame: Innovation as a Path to Fulfill Human Rights

While many respondents addressed the issue of rights in some way, much like in other sub-frames, there were contrasting views on the meaning of rights and how they should be secured. At root, a distinction could be made between arguments that foregrounded *individualistic economic* rights on the one hand, and *collective and political* rights on the other. The former placed an emphasis on the markets as the most empowering mechanisms of social change and on the rights of individuals to choose access technologies and innovations. Here, the emphasis is on the notion of "choice," indicating that end-users should have the freedom to choose from all available technologies. As one response illustrates,

> *taking the example of improved varieties, which are the result of technology and innovation, ISF would like each farmer around the world to have the possibility to make an informed choice about which seed will best suit their personal circumstances. [Helene Guillot, ISF]*

As we have seen already, farmers are sometimes framed as *primarily* business owners, and the right to access—or *choose*—from all available agricultural innovations was repeatedly claimed to be crucial to ensuring farmer livelihoods. Occasionally, such rights were framed in terms of "property rights,"

> *ISF emphasizes that effective intellectual property (IP) protection stimulates breeders to invest in the development and delivery of new varieties to provide farmers with the widest possible choices for productivity and success, thereby ensuring global food security. [Helene Guillot, ISF]*

As with the technology sub-frame, the main thrust here was a call to protect, not the rights of vulnerable peoples directly, but to ensure the property rights of technology developers so that a wider range of improved products can be made available to farmers. This reflects an approach that underlines technology developers as having exclusive rights to own, control and profit, and the ability of individual farmers to have access to the use of all available technologies as an inalienable right. Again, justification for this power is given, not purely in economic terms, but that doing so would help to deliver wider social goods, like "global food security."

In contrast to arguments in favor of individual economic rights, were those of collective political rights, such as the "right to food" and food sovereignty (defined as the right of all peoples "to define their own food and agriculture systems" (Nyeleni Movement for Food Sovereignty, 2007). The "stronger" formulations of these arguments were articulated in ways which highlighted the distorting impact of the innovation discourse on human and environmental rights. Some actively attempted to de-emphasize innovation altogether, claiming:

> *Rights is not another innovation. It is important to ground the entire analysis within the rights-based mandates of the CFS. Currently, Right-based innovations are included alongside other production systems, when they do not belong in that analysis. Rights provide a fundamental base that underpin all of SFS and FSN. [Maywa Montenegro, ARC]*

In doing so, these respondents illustrated the profound divisions in approach to innovation which, as the above quotation suggests, can easily flatten out important political dynamics, making human rights or agroecology appear like "options," rather than the moral foundations on which the socio-technical world ought to be built. Indeed, as another respondent put it,

> *Innovations should be considered as creative responses to challenging conditions and/or the mix of processes and practices that promote transitions to a new desired state. In the CFS context, the only innovations that should be considered are those whose explicit motive is the realization of the right to adequate food and the pursuit of food security and nutrition. [Stefano Prato, CFS]*

Whether the rights in view were economic or political in focus, all contributors were interested in how actors could be included in the innovation processes and systems, reflecting the now-prominent concern in the innovation discourse generally (Cf. OECD and "inclusive innovation"). However, differing conceptions of rights highlight deep-rooted divisions in the way that participation is imagined. On the surface there appeared to be similarities—for example, even those conceptualizing farmers as primarily *"business owners,"* also argued that "*decision-making for farmers should remain local." [Donald Moore, Global Dairy Platform]*—yet these decision-making processes were invariably contained within markets. Where political and collective rights were put forward, they tended to be much further reaching in scope, framing farmers not only as "beneficiaries," but active participants in defining what innovation means in each context. For example,

> *Any assessment rubric for successful innovation should therefore be democratically defined, co-developed, and led by rural peoples' ecological knowledge and practices. Rather than treating smallholder farmers as beneficiaries of aid, they should be seen as experts with knowledge that is complementary to formalized expertise. [Anisah Madden, AFSA]*

Such arguments could be distinguished in the way they understood innovation not as a "thing" whose value is implicit, but as a process whose aims must be continually assessed and revised, especially by those most affected by their potential impacts. Though both conceptions effectively forego a detailed definition of what innovation *is*, the reasons for this are quite different. Those using it to defend individualistic economic rights appears do so in a vague way: like Schumpeter, innovation is simply "doing things differently" as a way of bringing products to market, whatever their impacts. By contrast, those working on a basis of collective rights defer definition in an apparently deliberate way: what innovation is must be collectively and "democratically defined" and "co-developed" in specific contexts, and in close articulation with the social and environmental dynamics of that place. This market- vs. people-led distinction is often buried behind the seductive shimmer of "novel" technological innovation. In this discursive arena, we argue, the contrast between these two positions was brought powerfully to the fore, especially by those calling for us to reclaim and revise our understandings of what innovation means and what it is for.

THE FINAL HLPE REPORT AND BEYOND

The Final HLPE Report - A Shift in Framing

From December 2018 to February 2019, the HLPE committee considered and incorporated the views expressed through the online consultation on the V0 draft. These were used to develop a V1 draft which was then sent for expert peer review, revised again, and ultimately launched on July 3, 2019 in at the FAO Headquarters in Rome. While we did not conduct a full analysis of the report—focussing instead on the often-hidden discursive dynamics that played out through the individual interventions in the consultative process—some points are worth noting as they relate to the three innovation sub-frames. Perhaps the biggest shift between the V0 and V1 drafts involved a repositioning of the issue of human rights and the emphasis on the issue of agency. While in the V0 draft, "rights based approaches" were positioned alongside eight other proposed "approaches to innovation" in sustainable food systems, including "climate smart agriculture" and "agroforestry." In the final version, the authors shifted the framing of the report, positioning human rights as a master frame and demoting both agroecology and innovation, claiming "This report *starts from the recognition of human rights* as the basis for ensuring sustainable food systems" [emphasis added]. This could be seen in the report's call to add "the emerging concept of "agency" as a fifth pillar of food and nutrition security to capture the importance of people's participation in decision-making." Such a move highlights not only a strengthening of the rights agenda in this arena, but also the attempt to counter the tendency of the innovation frame to flatten out policy discourse to make things like human rights equivalent to—in some cases *co-terminus* with—commercial choice and economic freedoms. Further, the report also placed the notion of "transformation" more centrally in final report, a point that has since been contentious with governments who are wary of the ramifications and commitments demanded by a rights-based framing of transformation. Here, again, adopting an innovation framing is much safer and non-threatening for governments.

The report's approach to technology also registered an attempt to respond to challenges made in the consultation phase. Within its recommendations was the urge to move beyond the "technological paradigm" which has "become increasingly incompatible with present and future expectations." Elsewhere, however, there was still evidence of top down approaches to "technology transfer mechanisms" which, while focussed on "technologies in agroecological and other innovative approaches," were still framed in terms of technology "adoption [...] by farmers/producers" rather than prioritizing innovation *with* these actors.

After the Scaling Agroecology Process and the HLPE Report

Ultimately, the efforts in the 5 years leading up to the launch of the HLPE report marked a substantial opening for agroecology. On the one hand, there is evidence that the re-framing efforts have watered down and depoliticized the radical agroecology being advanced by social movement actors (Giraldo and Rosset, 2018). On the other, actors in the UN discursive space, including in the final HLPE report, have pushed the boundaries, arguing for food system transformation, and framing of agroecology in a way that reflects many of the tenets of food sovereignty (Loconto and Fouilleux, 2019). This has also resulted in deliberate promotion of specific transformative elements in civil society and government spaces, leading to further research, advocacy, and programming at multiple levels. The FAO's Scaling Up Initiative has included the allocation of institutional budget in FAO to agroecology with dedicated staff, the development of a global tool for monitoring agroecology (called TAPE), amongst other concrete benefits.

That said, it is also true that these successes have also met a significant backlash by proponents of the status quo and there are now moves to attack, discredit, and exclude agroecology in the UN system. Firstly, the US government continued to obstruct the HLPE report after its release, blocking the utilization of the findings in the Food Systems and Nutrition Guidelines and also objecting to the appointment of the Iranian Permanent Representative as the Rapporteur of the Policy Convergence on the HLPE report. This essentially blocked and delayed the actual implementation of the results, "undermining well-established and agreed-on procedures and protocols of the CFS" (Agroecology Working Group of the Civil Society Mechanism of the UN Committee on Food Security., 2019). Eventually, under pressure from other member states, the US conceded, and the rapporteur was able to advance the policy convergence.

Secondly, while the HLPE report ended up being clearly focused on the need to support agroecology and a food system transformation, the policy recommendations developed during the policy convergence watered down the messages of the report (Committee on World Food Security, 2020). While the HLPE report incorporated many points that would indeed support agroecology (e.g., shifting funds to agroecology research, supporting cooperatives, etc.), the overall call for food system transformations based on an agroecology approach were substantially diminished. The positioning of "agency" and rights was decentred. Where human rights are invoked, there aren't calls to guarantee or to enforce human rights, but rather to "recognize," "respect" or "promote" (Civil Society Mechanism for relations to the Committee on World Food Security (CSM), 2020). Further, despite a clear distinction in the HLPE report that agroecology was a vital approach that stands apart from "other innovations," the recommendations make generalized calls to support "agroecological approaches and other innovations." The policy recommendations thus continue to call for many of the business-as-usual approaches critiqued in the actual report, including approaches that "optimize agrochemical usage." It positions agroecology as a complimentary approach to tweaks to conventional agriculture, sustainable innovation, climate smart agriculture, and other approaches that were argued in the HLPE report to be largely incompatible.

Third, at a broader level, the strong assertation of a rights-based and food sovereignty-based agroecology prompted a strong back-lash by proponents of green revolution style agricultural development. For example, the USA Permanent Representative to the United Nations Agencies for Food and Agriculture in Rome Kip Tom has made claims that the FAO has been co-opted by European NGOs, "spreading mis-information" about GMOs and pesticides, and disparaging approaches to agriculture that don't conform to "American values." Using this platform he has made arguments for "the innovation imperative," which positions "progress and innovation as obvious goods" which he describes as the acceptance of American values and technologies (Tom, 2020). In similar move, the Gates Foundation-funded "Cornell Alliance for Science," whose main mission is to promote biotechnology in Africa, has also attacked agroecology as anti-science and irrational, claiming that it denies farmers the rights to access innovations, and in contrast, adopts an individualistic market-centered approach to rights (Conrow, 2020).

Finally, In October 2019, the UN Secretary-General's official announced a World Food Systems Summit to be held in New York in 2021. This major global summit aims to secure global

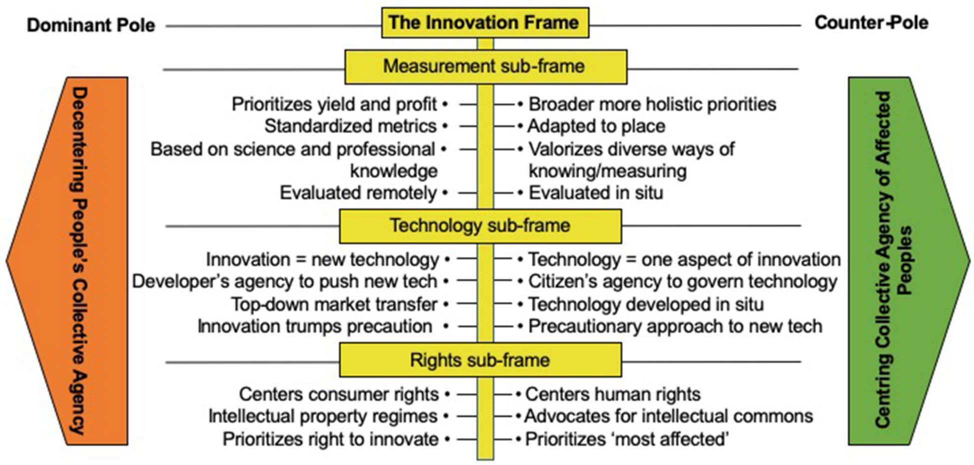

FIGURE 1 | The sub-frames of the innovation frame have both a "counter-pole" that centers the collective agency of people and a dominant pole that decenters people's collective agency.

commitments to address hunger, diet-related health and the environment. It is to be led by the World Economic Forum and has been widely critiqued for choosing a champion of biotechnology to chair the event. Although there are references to "multi-stakeholder" participation, the role of civil society and the issue of human rights have been effectively marginalized (Fakhri, 2020). Such events combine to remind us that while progress can be made shaping particular discursive arenas, the broader discursive landscape must also be considered. Indeed, more than simply being hostile, gains within specific discursive arenas can even prompt significant backlashes in the external environment. At time of writing the extent and impact of this 'reaction' remains to be seen.

CONCLUSIONS

Agroecology is being presented as an alternative vision of food and farming and, indeed, is gaining traction in local, national and global discourse. It is, however, a hotly contested term and its meaning and potential is being constructed through the interactions of a wide range of actors with different political agendas. Our study probed the ways that the innovation frame was mobilized in the United Nations debates on agroecology. We found that innovation can serve to contain and co-opt the transformative potential of agroecology (Anderson et al., 2019), and was intentionally mobilized by detractors of agroecology for that very purpose.

Although the ecological principles that underlie agroecology are critical, it is the emphasis on the collective knowledge, rights and agency of the most affected that separates agroecology from production-oriented proposals like climate smart agriculture and sustainable intensification (Pimbert, 2017). As a perspective rooted in the logic of increased production and technological modernization, our study showed how the innovation frame routinely overlooks and diminishes the social agency of individuals and communities—or as the HLPE themselves define it, the ability to, "define their desired food systems and nutritional outcomes, and to take action and make strategic life choices in securing these" (HLPE, 2019).

We identified three sub-frames of the innovation frame that played out in the discursive arena of the FAO. These focused on innovation in relationship with: evidence; technology; and rights. Within each of these sub-frames, it is clear that there were competing poles which can be understood through the lens of agency. On the one end, innovation is used to reinforce dominant conceptions of agency—overwhelmingly those exercised by individuals through markets—in ways that maintain the political status quo. On the other pole, proponents of agroecology put forward a counter-discourse for the collective rights and agency of the "most affected" as the basis for agroecological innovation (**Figure 1**). The agroecological approach challenges many of the assumptions that are bound up in the innovation imperative including: the centrality of agribusiness, the hegemony of abstract indicators, the notion that technology is the most important form of innovation and the casting of food producers as end-users or consumers. Centring the collective protagonism, voice, agency and autonomy of food producers and their communities in decision-making on the governance of food systems is a radical shift that is by in large side-lined by the innovation imperative.

The role of the innovation frame in undermining collective agency, and thus the political aspects of agroecology, might not be that surprising given its "Schumpeterian" origins and linked innovation systems in capitalist and neoliberal economics. The word innovation is used by many different actors for contrasting purposes, yet over almost a century of common usage, the term has become the friendly face of aggressive competition and freewheeling technological modernization. The innovation framing has consistently foregrounded the advantages to be gained by inventors, innovators, and intellectual property rights holders, while downplaying or masking the often-dire social and ecological consequences of technology, largely borne by the most disadvantaged. This dynamic continues to play out in deleterious ways in global food systems and beyond. To this end, we recommend that advocates of agroecology—and other holistic, political, and radical proposals for change—avoid the innovation frame in debates on policy, research, and visioning for the future, wherever possible. Where it is unavoidable, understanding the discursive dynamics across the sub-frames outlined in this article (**Figure 1** for summary) can help understand, contest, and propose alternatives to the problematic dominant framing typical of mainstream innovation discourse.

Like sustainable agriculture, organics, and other related terms that have had their day in the sun as candidates for framing transformative change in the food system, the transformative thrust of "agroecology" is not a given. In many cases, concepts that have been initiated in a transformative perspective become warped and re-molded as they gain prominence and institutional uptake. This article highlights the framing of agroecology innovations as a potential strategy for undermining collective politics and the reassertion of a market fundamentalism. Re-centring collective agency as the basis for evaluating innovations is a seemingly subtle, but vital, discursive maneuver being led by social movements, and a strategy that has already led to important outcomes in the FAO for agroecology. While recent attacks on agroecology outside the HLPE discursive arena should cause real concern, substantial gains have been made to bring radical arguments into these institutional spaces and to make both discursive and material gains as a result.

Innovation—often framed as novel technologies, transferred to users, to increase yield and profit—is an imperative only from the perspective of those fastened to the treadmill of expensive and privately-owned technologies. In this article, we intended to unveil the oft-hidden politics which lies beneath the language of innovation, and the power and erasure that occurs through the demands of the "innovation imperative." Whereas, agroecology has been advanced as a radical alternative to industrial agriculture, the innovation discourse often undermines its potential. A more pressing imperative today is to adopt a language and practice that enables us to escape from the discursive and material hold of industrial agriculture. These political discursive strategies and struggles are one key aspect of the desperately needed societal transformations that foreground the collective rights and agency of food producers and citizens ahead of the profit motive.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found at: http://www.fao.org/fsnforum/cfs-hlpe/discussions/agroecology_innovation-v0.

AUTHOR CONTRIBUTIONS

Both authors contributed equally to the analysis and authorship of this article.

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REFERENCES

Agroecology Working Group of the Civil Society Mechanism of the UN Committee on Food Security. (2019). *Worldwide Civil Society Organizations Denounce US Government Obstruction of the UN Committee on World Food Security (CFS) Policy Convergence Process for Solutions to Food Security and Nutrition Crisis*. Available online at: https://www.iatp.org/documents/worldwide-civil-society-organizations-denounce-us-government-obstruction-un-committee-0 (accessed February 2, 2021).

Anderson, M. (2020). "Innovation for whom," in *Transformation of our Food Systems,* eds H. R. Herren, B. Haerlin and IAASTD+10 Advisory Group (Berlin/Zurich: Zukunftsstiftung Landwirtschaft/Biovision), 33–36.

Anderson, C. R., Bruil, J., Chappell, M. J., Kiss, C., and Pimbert, M. P. (2019). From transition to domains of transformation: getting to sustainable and just food systems through agroecology. *Sustainability* 11:5272. doi: 10.3390/su11195272

Anderson, C. R., Pimbert, M., Chappell, M. J., Brem-Wilson, J., Claeys, P., Kiss, C., et al. (2020a). Agroecology now - connecting the dots to enable agroecology transformations. *Agroecol. Sustain. Food Syst.* 44, 561–565. doi: 10.1080/21683565.2019.1709320

Anderson, C. R., Bruil, J., Chappell, M. J., Kiss, C., and Pimbert, M. P. (2020b). *Agroecology Now! Transformations Towards More Just and Sustainable Food Systems*. Cham: Palgrave MacMillan.

Baker, S., and Mehmood, A. (2015). Social innovation and the governance of sustainable places. *Local Environ.* 20, 321–334. doi: 10.1080/13549839.2013.842964

Barrett, H., and Rose, D. C. (2021). Perceptions of the fourth agricultural revolution: what's in, what's out, and what consequences are anticipated? *Sociol. Ruralis*. 1–28. doi: 10.1111/soru.12324

Bellwood-Howard, I., and Ripoll, S. (2020). Divergent understandings of agroecology in the era of the African green revolution. *Outlook Agric.* 49, 103–110. doi: 10.1177/0030727020930353

Berthet, E. T. A., Barnaud, C., Girard, N., Labatut, J., and Martin, G. (2015). How to foster agroecological innovations? A comparison of participatory design methods. *J. Environ. Plan. Manag.* 59, 280–301. doi: 10.1080/09640568.2015.1009627

Brand, S. (2010). (eds.). *Whole Earth Discipline*. New York, NY: Penguin.

Civil Society Mechanism for relations to the Committee on World Food Security (CSM). (2020). *Zero Draft of the Policy Recommendation on "Agroecological and other innovative approaches" CSM's Comments* (Rome).

Committee on World Food Security. (2020). *Zero Draft of Policy Recommendations on Agroecological and Other Innovative Approaches for Sustainable Food Systems that Ensure Food Security and Nutrition*. Rome: CFS.

Conrow, J. (2020). Agroecology must be based in reality, not romanticism, panelists. *Cornell Alliance Sci*. Available online at: https://allianceforscience.cornell.edu/blog/2020/10/agroecology-must-be-based-in-reality-not-romanticism-panelists-agree/

El Bilali, H. (2019). Innovation-sustainability nexus in agriculture transition: case of agroecology. *Open Agric.* 4, 1–16. doi: 10.1515/opag-2019-0001

El Bilali, H. (2018). Relation between innovation and sustainability in the agro-food system. *Italian J. Food Sci.* 30, 200–225. doi: 10.14674/ijfs-1096

Fairclough, N. (2013). *Critical Discourse Analysis: A Critical Study of Language*. London: Routledge.

Fakhri, M. (2020). *Agenda Item 3 A/HRC/46/33. Special Rapporteur on the Right to Food Report to the Human Rights Council*. Available online at: https://undocs.org/Home/Mobile?FinalSymbol=A%2FHRC%2F46%2F33&Language=E&DeviceType=Desktop (acceassed December 24, 2020).

FAO (2016). *Proceedings of the FAO International Symposium on the Role of Agricultural Biotechnologies in Sustainable Food Systems and Nutrition.* Rome: FAO.

FAO (2018). *Catalysing Dialogue and Cooperation to Scale up Agroecology: Outcomes of the FAO Regional Seminars on Agroecology*. Rome: FAO.

FAO (2020). *Our Priorities: The FAO Strategic Objectives*. Rome: FAO.

Foucault, M. (1969). *The Archaeology of Knowledge.* Paris: Éditions Gallimard.

Fouilleux, E., Bricas, N., and Alpha, A. (2017). 'Feeding 9 billion people': global food security debates and the productionist trap. *J. Europ. Public Policy* 24**,** 1658–1677. doi: 10.1080/13501763.2017.1334084

Fuchs, D., and Glaab, K. (2011). Material power and normative conflict in global and local agrifood governance: the lessons of 'Golden Rice' in India. *Food Policy* 36**,** 729–735. doi: 10.1016/j.foodpol.2011.07.013

Garnett, K., Van Calster, G., and Reins, L. (2018). Towards an innovation principle: an industry trump or shortening the odds on environmental protection? *Law Innovat. Technol.* 10**,** 1–14. doi: 10.1080/17579961.2018.1455023

Geels, F. W., Tyfield, D., and Urry, J. (2014). Regime resistance against low-carbon transitions: introducing politics and power into the multi-level perspective. *Theory Culture Soc.* 31, 21–40. doi: 10.1177/0263276414531627

Giraldo, O. F., and McCune, N. (2019). Can the state take agroecology to scale? public policy experiences in agroecological territorialization from latin america. *Agroecol. Sustain. Food Syst.* 43, 785–809. doi: 10.1080/21683565.2019.1585402

Giraldo, O. F., and Rosset, P. M. (2018). Agroecology as a territory in dispute: between institutionality and social movements. *J. Peasant Stud.* 45**,** 545–564. doi: 10.1080/03066150.2017.1353496

González de Molina, M., Petersen, P. F., Peña, F. G., and Capor, F. R. (2019). *Political Agroecology: Advancing the Transition to Sustainable Food Systems.* Boca Raton, FL: CRC Press.

Guthman, J. (2004). *Agrarian Dreams: the Paradox of Organic Farming in California.* Berkeley: University of California Press.

Hajer, M., and Versteeg, W. (2005). A decade of discourse analysis of environmental politics: achievements, challenges, perspectives. *J. Environ. Policy Plann.* 7, 175–184. doi: 10.1080/15239080500339646

HLPE (2018). *Syhnthesis Report on V0 Draft Consultation - Agroecological Approaches and Other Innovations for Sustainable Agriculture and Food Systems that Enhance Food Security and Nutrition*. Rome: CFS High Level Panel of Experts.

HLPE (2019). *Agroecological and Other Innovative Approaches for Sustainable Agriculture and Food Systems that Enhance Food Security and nutrition*. Rome: CFS High Level Panel of Experts.

IAASTD (2009). *Agriculture at a Crossroads: Report of the International Assessment of Agricultural Knowledge, Science, and Technology.* Washington, DC: Library of Congress.

Joly, P. (2018). *Note de Recherche IFRIS N°6: Innovation and the Problem of Values*. Paris: L'IFRIS.

Klerkx, L., and Rose, D. (2020). Dealing with the game-changing technologies of Agriculture 4.0: How do we manage diversity and responsibility in food system transition pathways? *Global Food Security* 24:100347. doi: 10.1016/j.gfs.2019.100347

Kothari, A., Salleh, A., Escobar, A., Demaria, F., and Acosta, A. (2019). *Plurivers: A Postdevelopment Dictionary.* New Delhi: Tulika Books.

Laforge, J. M. L., Anderson, C. R., and McLachlan, S. M. (2016). Governments, grassroots, and the struggle for local food systems: containing, coopting, contesting and collaborating. *Agric. Human Values* 34**,** 663–681. doi: 10.1007/s10460-016-9765-5

Lajoie-O'Malley, A., Bronson, K., van der Burg, S., and Klerkx, L. (2020). The future(s) of digital agriculture and sustainable food systems: an analysis of high-level policy documents. *Ecosyst. Serv.* 45:101183. doi: 10.1016/j.ecoser.2020.101183

Levidow, L., and Papaioannou, T. (2018). Which inclusive innovation? competing normative assumptions around social justice. *Innov. Dev.* 8**,** 209–226. doi: 10.1080/2157930X.2017.1351605

Levidow, L., Pimbert, M., and Vanloqueren, G. (2014). Agroecological research: conforming—or transforming the dominant agro-food regime? *Agroecol. Sustain. Food Syst.* 38**,** 1127–1155. doi: 10.1080/21683565.2014.951459

Loconto, A. M., and Fouilleux, E. (2019). Defining agroecology. *Int. J. Sociol. Agric. Food* 25, 116–137. doi: 10.48416/ijsaf.v25i2.27

López-García, D., Calvet-Mir, L., Di Masso, M., and Espluga, J. (2018). Multi-actor networks and innovation niches: university training for local agroecological dynamization. *Agric. Human Values* 36, 567–579. doi: 10.1007/s10460-018-9863-7

Marchetti, L., Cattivelli, V., Cocozza, C., Salbitano, F., and Marchetti, M. (2020). Beyond sustainability in food systems: perspectives from agroecology and social innovation. *Sustainability* 12:7524. doi: 10.3390/su12187524

Maughan, C., Anderson, C., and Kneafsey, M. (2020). A five-point framework for reading for social justice: a case study of food policy discourse in the context of brexit britain. *J. Agric. Food Syst. Commun. Dev.* 9, 1–20. doi: 10.5304/jafscd.2020.093.024

Méndez, V. E., Bacon, C. M., and Cohen, R. (2013). Agroecology as a transdisciplinary, participatory, and action-oriented approach. *Agroecol. Sustain. Food Syst.* 37, 3–18. doi: 10.1080/10440046.2012.736926

Meynard, J.-M., Jeuffroy, M.-H., Le Bail, M., Lefèvre, A., Magrini, M.-B., and Michon, C. (2017). Designing coupled innovations for the sustainability transition of agrifood systems. *Agric. Syst.* 157, 330–339. doi: 10.1016/j.agsy.2016.08.002

Miles, C. (2019). The combine will tell the truth: on precision agriculture and algorithmic rationality. *Big Data Soc.* 6, 1–12. doi: 10.1177/2053951719849444

Moeller, N. I., and Devlaux, F. (2020). *Finance for Agroecology: More Than Just a Dream?* Brussels: CIDSE.

Montenegro de Wit, M., and Iles, A. (2016). Toward thick legitimacy: creating a web of legitimacy for agroecology. *Elementa Sci. Anthropocene* 4:000115. doi: 10.12952/journal.elementa.000115

Mummery, J., and Mummery, J. (2019). Transformative climate change adaptation: bridging existing approaches with post-foundational insights on justice. *Local Environ.* 24, 919–930. doi: 10.1080/13549839.2019.1656180

Nyeleni (2015). *Declaration of the International Forum for Agroecology*. Available online at: http://www.foodsovereignty.org/forum-agroecology-nyeleni-2015/ (accessed January 25, 2021).

Nyeleni Movement for Food Sovereignty (2007). *Nyéléni Declaration for Food Sovereignty*. Available online at: http://nyeleni.org/spip.php?article290 (accessed January 25, 2021).

O'Brien, K. (2016). "Climate change adaptation and social transformation," in *International Encyclopedia of Geography: People, the Earth, Environment and Technology*, ed D. Richardson (Oxford: John Wiley & Sons, Ltd), 1–8.

OECD (2015). *The innovation Imperative: Contributing to Productivity, Growth and Well-Being.* Paris: OECD.

Pansera, M., and Owen, R. (2018). *Innovation and Development: The Politics at the Bottom of the Pyramid*. Hoboken, NJ: John Wiley & Sons.

Pimbert, M. (2017). Agroecology as an alternative vision to conventional development and climate-smart agriculture. *Development* 58, 286–298. doi: 10.1057/s41301-016-0013-5

Pimbert, M. P., and Moeller, N. (2018). Absent agroecology aid: on UK agricultural development assistance since 2010. *Sustainability* 10:505. doi: 10.3390/su10020505

Quist, D. A., Heinemann, J. A., Myhr, A. I., Aslaksen, I., and Funtowicz, S. (2013). "Hungry for innovation: pathways from GM crops to agroecology," in *Late Lessons from Early Warnings: Science, Precaution, Innovation*, ed D. Gee (Brussels: European Environmental Agency), 458.

Rivera-Ferre, M. G. (2018). The resignification process of agroecology: competing narratives from governments, civil society and intergovernmental organizations. *Agroecol. Sustain. Food Syst.* 42, 666–685. doi: 10.1080/21683565.2018.1437498

Rosset, P. M., and Altieri, M. A. (2017). *Agroecology: Science and Politics.* Winnipeg: Fernwood.

Rover, O., de Gennaro, B., and Roselli, L. (2016). Social innovation and sustainable rural development: the case of a Brazilian agroecology network. *Sustainability* 9:3. doi: 10.3390/su9010003

Schiller, K. J. F., Klerkx, L., Poortvliet, P. M., and Godek, W. (2019). Exploring barriers to the agroecological transition in Nicaragua: a technological innovation systems approach. *Agroecol. Sustain. Food Syst.* 44**,** 88–132. doi: 10.1080/21683565.2019.1602097r

Schumpeter, J. A. (2005). *Business Cycles: A Theoretical, Historical, and Statistical Analysis of the Capitalist Process.* Eastford, CT: Martino Publishing.

Scoones, I., Newell, P., and Leach, M. (2015). "The politics of green transformations," in *The Politics of Green Transformations*, eds I. Scoones, M. Leach, and P. Newell (London: Routledge), 19–42.

Seyfang, G., and Smith, A. (2007). Grassroots innovations for sustainable development: towards a new research and policy agenda. *Env. Polit.* 16, 584–603. doi: 10.1080/09644010701419121

Snow, D. A., and Benford, R. D. (1992). "Master frames and cycles of protest," in *Frontiers in Social Movement Theory,* eds A. D. Morris and C. M. Mueller (New Haven, CT: Yale University Press), 133–155.

Steinberg, M. W. (1998). Tilting the frame: considerations on collective action framing from a discursive turn. *Theory Soc.* 27, 845–872. doi: 10.1023/A:1006975321345

Stirling, A. (2014). From sustainability to transformation: dynamics and diversity in reflexive governance of vulnerability. *SSRN* 305–332. doi: 10.2139/ssrn.2742113

Stuiver, M. (2006). "Highlighting the retro side of innovation and its potential for regime change in agriculture," in *Between the Local and the Global (Research in Rural Sociology and Development*. Vol. 12, eds T. Marsden and J. Murdoch (Bingley: Emerald Group Publishing Limited), 147–173.

Tom, K. (2020). *Speech at U.S. Department of Agriculture's (USDA) 2020*. Arlington, VA: Agricultural Outlook Forum.

Uphoff, N. (2013). *Agroecological Innovations: Increasing Food Production with Participatory Development*. New York, NY: Routledge.

Van Dyck, B., Kenis, A., and Stirling, A. (2019). "The GMO shall not be refused. talking back to the technosciences," in *Historical Materialism Sixteenth Annual Conference* (London).

van Hulst, F., Ellis, R., Prager, K., and Msika, J. (2020). Using co-constructed mental models to understand stakeholder perspectives on agro-ecology. *Int. J. Agric. Sustain.* 18, 172–195. doi: 10.1080/14735903.2020.1743553

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Theoretical and Conceptual Considerations for Analyzing Social Interfaces in Agroecosystems

Felipe Gallardo-López[1], *Ariadna Linares-Gabriel*[1] and *Mario Alejandro Hernández-Chontal*[2]*

[1] *Postgrado en Agroecosistemas Tropicales, Colegio de Postgraduados, Campus Veracruz, Veracruz, Mexico,* [2] *Facultad de Ciencias Agrícolas, Universidad Veracruzana, Xalapa, Mexico*

The current framework of agroecosystem (AES) knowledge focuses on a systemic approach or static structures rather than on dynamic processes that are defined historically. The hypothesis is that agroecosystems are the product of the interdependence of a diversity of actors (present and absent) and, therefore, constitute complex social interfaces, which, in order to address them, require a new understanding of the centrality of the actors and their capacity for agency. Then, regarding this complexity, some aspects are not clearly defined in the systemic approach which need to be more explicit such as: (a) the implicit psychosocial aspects and (b) the relationships with their social environment, how these affect them and are affected by them. The purpose of this document is to suggest a theoretical and conceptual approach to correct these unclear areas. First, the centrality of actors (including their agency capacity) in the AES is recognized. Besides, their interdependence with the diversity of actors (present and absent) and therefore the need to analyze the AES complex social interfaces.

Keywords: agroecosystems, agroecology, actor-oriented approach, social interface, agency

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****Correspondence:***
Mario Alejandro Hernández-Chontal
mariohernandez03@uv.mx

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INTRODUCTION

Agriculture is a key development, mainly for food production, for its origin and its effects on the population and society (Sarker, 2017). It is a complex activity that involves (1) the production of food and fiber (based on technological factors, natural resource endowments and capital impulses), (2) processes linked to the effects it produces on societies and ecosystems (Sicard, 2009). According to Gallardo-López et al. (2018), this refers to a complex society-nature relationship. As social actors become relevant, the challenge is to generate new ways of seeing and researching agriculture to consider disciplinary interfaces (Gallardo-López et al., 2019).

This complexity is accentuated in the modern age because farmers are operating in an increasingly complex and rapidly changing environment. They must balance conflicting demands involving social, political, economic, technological and environmental aspects (Hendrickson et al., 2008). Thus, this involves the traditional agrarian mode (peasant) and the agro-industrial mode (conventional) as two ways of conceiving, managing and using agroecosystems (Martínez, 2004). Furthermore, it implicates aspects related to increasing food productivity, resilience to climate change and reducing carbon emissions. In agroecosystems, unequal power relations, inequality and social injustice must also be taken into account and included in the policy and practice of agriculture (Chandra, 2017).

In fact, it is important to consider that an agroecosystem is both ecologically and socially important and that a genuinely transformative change in our food and agricultural systems is based on social and political change. Agroecology is here, the action-oriented approach to participate in this process (Gliessman and Ferguson, 2021). This involves several transitions at the social, biological, economic, cultural, institutional and political levels (Tittonell, 2019; Tittonell et al., 2020). It should be noted that agroecological science was originally developed by applying ecological principles to agricultural systems and then, by integrating social and political aspects that affect production in agriculture (Mason et al., 2020). Today, agroecology provides a path toward a new agriculture, one which goes beyond the routine of pesticides, enriches the matrix of nature and revitalizes and creates alternative systems of production (Altieri and Nicholls, 2020). According to these authors, it is evident that current and future agroecosystems have multiple challenges and the vision and transformative action needed to achieve such challenges lies in social change.

However, after analyzing the origin and evolution of agroecological science and its unit of study, agroecosystems, social aspects are later incorporated and still addressed as non-dynamic and ahistorical structures –as will be explained in the next section. In addition, contemporary research in AES focuses on increasing agricultural productivity disregarding the relevance of social aspects (Gallardo-López et al., 2020). Principally the psychosocial aspects implicit in agro-ecosystems (AES), their approach, as well as the relationship with the environment which affect and are affected, are not clearly defined. Therefore, this theoretical and conceptual proposal is suggested to address these unclear areas. The central hypothesis is that agroecosystems are the product of the interdependence of a diversity of actors (present and absent) and therefore constitute complex social interfaces, which require a new understanding of the centrality of the actors and their capacity for agency. Therefore, this document aims to provide some preliminary theoretical and conceptual considerations to address social interfaces in agroecosystems. Initially, the implications on the evolution of the agroecosystems concept are discussed. The centrality of actors is analyzed from an actor-oriented approach followed by the concepts of agency and social interfaces. Finally, the psychosocial and relational processes are understood in the context of the complexity of the AES.

IMPLICATIONS FOR THE EVOLUTION OF THE AGROECOSYSTEM CONCEPT

Although this work is not intended to provide a historical overview of the concept of agroecosystems (AES), it is important to review the approaches used to show the implications, scope and limitations of such evolution. Initially, agroecosystem concepts considered the components and functions of natural ecosystems, including local knowledge and production strategies based on ecological principles (ecological pest management, crop association and agroforestry systems) (Altieri, 1999; Gliessman, 2011). Then, it was framed in the systems approach and its main contribution was the application of the concept of hierarchies allowing the identification of different levels of agroecosystems (plant, crop, farm, region and larger scales) until transferring to a broader vision systems including ecological, economic and political aspects which recognizes the leading role that farmers that (Gallardo-López et al., 2018).

The concept of agro-ecosystems evolved along with systems thinking to complex systems thinking as described by Casanova et al. (2016). The authors mention that complex systemic thinking provides radical approaches to understand contemporary agricultural problems, but they have been ignored due to the scarce theoretical reflexivity, and the predominance of an analytical and empirical approach. Systems thinking has developed integrated analyses that favor the study of the components of the AES but not their interdependencies, hence it prevents them from being understood as a whole. In this sense, although even from the systemic conception, Gallardo López (2002) considered that the agroecosystem is a system which is a, product of the relationship between human and nature in which structure there is a socioeconomic component (the producer and his family) and another productive component (the farm).

Other concepts explicitly consider the complexity of the agroecosystem. In this regard, Sarandón (2014) mentions that agroecosystems are complex systems with biological components that have been distributed in time and space, interacting with socio-cultural components (objectives, rationalities, knowledge and farmers' culture). The complexity is determined by their components and the interrelationships between them within a management framework in which the human being is intimately inserted in a socio-cultural context that determines the way one makes his decisions. In line with this, Cruz-Bautista et al. (2019) conceptualize the agroecosystem as an abstraction or a cut-out of the agricultural reality, which is managed by a controller who makes the decisions concerning its structure and functioning.

From its practical notion, the agroecosystem is situated in an analysis toward the redesign of agro-ecosystems that work on the basis of a set of ecological principles. These comprise interaction, complementarity, and relationship in systems that provide the capacity to resist the problems that industrial agriculture controls with an impressive variety of inputs and practices (Gliessman, 2012). These principles are based on physical and biological aspects considered from the initial conceptions. From this perspective, Josol and Montefrio (2013) consider agro-ecosystems from the concept of resilience to analyze their response to external changes. Moreover, the authors claim that exposure to low-level disturbances promotes heterogeneity in the landscape and promotes renewal and reorganization within the system. It is important to emphasize that the most recognized and accepted literature uses the agroecosystem as a scale of analysis in agroecology (Gallardo-López et al., 2018) and that the conjunction of the agroecosystem and agroecological practices is called a mixed conception (Fernández González et al., 2020). The authors indicate that in this mixed conception, there is no unanimous understanding of transdisciplinary approaches and few studies investigate their implementation. Mason et al. (2020) propose analyzing the social and political problems affecting production agriculture and incorporating knowledge from various sources. However, they refer to the agroecosystems as studies conducted in the tropics with a focus on crop production and biodiversity.

There are also reflections on the analysis of agroecosystems with emphasis on autopoietic social systems. From this theoretical-conceptual perspective, the agroecosystem is a conceptual model that represents the agricultural reality, whose psychic system (producer) is the recipient of the autopoiesis of the agricultural system. Autopoiesis which is fed by the information that is communicated to it through the mass media (radio, TV, written press, internet), symbolically generalized media (money) and by the interaction systems (conversations held between two or more producers, producers and technicians, producers and institutional representatives, etc.). Such interactions provide them with new and valuable information that is used as a reference in decisions regarding the management of their agroecosystems (Casanova et al., 2016). It is also a model that represents the effects of autopoiesis, that of "subsistence, transitional and commercial production" systems. An approach that makes it possible to understand why a series of management practices are used by producers to modify ecosystems located in different geographic spaces for the purpose of producing food and raw materials (Casanova-Pérez et al., 2015).

While these abstractions recognize the farmer as a psychic system, in practice they place he as a passive subject who receives external information to be able to manage decisions in the agroecosystem. For this reason, it is needed to show a broader notion of people's behavior, mainly as active subjects with the capacity to construct their own reality, in line with what has been called in development sociology as the "Actor-Oriented Approach" (Long, 2001). Thus, it is necessary to first understand why they do what they do (Cittadini and Pérez, 1996).

Therefore, to identify and solve problems of the object of study of agroecology (nature-society relationship) such as agroecosystems, a greater dialogue between the abstract and the empirical is suggested. It is still pending the understanding of agriculture from different perspectives oriented to the use of paradigms in which the social actors, their development and the impacts of their social tasks are considered the main axis of the study (Gallardo-López et al., 2018). The lessons learned from this analysis concern this look toward complexity with the purpose of responding to the problems of the current and future agricultural reality through the concept of AES. It should not only be framed in the productive process, it must involve environmental, economic, social and political processes and certainly, the cultural context. A theoretical and conceptual evolution of the concept of AES is evident, which is supported by the contributions of the various authors cited in this section. However, this evolution is centered on a systemic approach or static structures and not on dynamic processes that are defined historically. In this current framework of agroecosystem knowledge, the assumption that agroecosystems are the product of the interdependence of a diversity of actors (present and absent) and therefore constitute complex social interfaces becomes relevant, and that in order to address them it is necessary to recognize the centrality of the actors and their capacity for agency. Therefore, within the approaches from the perspective of complexity, there are still aspects that need to be made explicit, mainly related to the implicit psychosocial aspects and the relationships with their social environment that affect and are affected.

THE CENTRALITY OF THE ACTORS IN THE AGROECOSYSTEM

As it was mentioned above, these psychosocial processes need to be focused on the actors. In order to do this, it is important to clarify the notion of actors and to recognize that farmers, and the actors with whom they interact, are social actors with agency – this is further explained –. The main purposes of actor-oriented methodologies are to clarify how actors attempt to create space for their own "projects" and to determine what elements contribute to or impede the successful creation of such room for maneuver (Leeuwis et al., 1990). The actor-centered approach developed by Long (2007) is used to explore how social actors, whether local or external, engage in intertwined battles for resources, meanings, control and institutional legitimacy in particular arenas. It implies a vision of social construction of change and continuity in which a society through actions and perceptions transforms a world of diverse and intertwined actors. It is characterized by being more dynamic –a counterpoint to structural analysis– since it helps to understand social change, it emphasizes the interaction and determination of internal-external factors and relationships, and recognizes the central role played by human action and consciousness (Long, 1990).

Social actors are all those social entities that can be said to have agency, in the sense of the capacity to know and assess problematic situations and to organize "appropriate" responses. These entities can take a variety of forms: individual subjects, informal groups or interpersonal networks, organizations, groupings, and what sometimes are described as macro actors (e.g., the government of a particular nation, a church, or an international organization) (Long, 2015a, p. 77–96). By emphasizing the voices and experiences of individual actors and their own knowledge of development and modernity, one can focus on the local, everyday practicalities of making a living and how people defend them (Turner, 2012).

A variety of social actors interact within the AES. Some are local, such as the farmers themselves, local authorities, associations and organizations. External actors, some acting locally, such as technicians, buyers, distributors, policy implementers, and other external acting in broader spheres, such as international organizations, the state, programs and projects designed in the governmental spheres. Although there may be other actors, this only shows an example of how a diversity of actors intervene in agroecosystems, all of them with the capacity for agency. If we talk about actors, we recognize the AES can be referred to as psychosocial processes from an actor-centered perspective. Therefore, this perspective requires a detailed ethnographic understanding of everyday life and the processes by which images, identities and social practices are shared, discussed, negotiated and sometimes rejected by the various actors involved (Long and Liu, 2009). Thus, focusing on the actor makes it possible to analyze the way in which different social forms develop, in the same or similar structural circumstances, that affect the way actors try to face or cope with certain situations (Roldán-Rueda, 2020).

This perspective supports the development of an empirical approach to psychosocial aspects in agroecosystems, taking into consideration the concept of human agency as a core part of this actor-centered perspective. In this way, it is proposed that AES are the product of a set of intertwined agencies; being conceived as a set of social, cultural and material elements, centered on the actor and rescuing the lived experience of the actors (Long, 2007). An important methodological guideline of the actor-oriented approach is to identify relevant actors without starting from preconceived notions of uniform actor categories or classes. Then, following this approach, the situated social practices of the actors are ethnographically documented including the way in which social relations, technologies and other resources (such as discourses and texts) are deployed (Hebinck et al., 2001).

Thus, if we take into account the technologies and material resources that are explicit and tangible in the agroecosystem, it is necessary to return to the notion of Actants. Long (2015b) in his work "*Activities, Actants and Actors: Theoretical Perspectives on Development Practice and Practitioners*" mentions that only actors are able to put actants into circulation. The precursor of "actants" was Latour (1996) who defined a symmetry of human and non-human components, showing how technologies, discourses (verbal and non-verbal) and other texts, material resources, symbolic elements, government policies, and human and non-human ways of life enter the development scene. In short, actants encompasses human actants (individuals and groups) and non-human actants (things, machines and other organisms) (Larrión, 2019). Therefore, discussing agency will not only include the actors present in the agroecosystems but also explicit tangible aspects such as seeds, fertilizers, machinery, irrigation systems, credit and development programs, to mention a few.

PSYCHOSOCIAL APPROACH IN AGROECOSYSTEMS

For the psychosocial approach in AES the essential element is the concept of agency as mentioned above. According to Long (2007), the notion of human agency is based on an anthropological and historical vision and the contribution of micro-sociology that touches the sphere of everyday life and it considers the influence exerted in this sphere by actions at the macro-social level. Long takes up the concept of human agency from the structuration theory of Giddens (2011), for the latter author, agency is the capacity of individuals to act independently and make their own choices freely.

In Norman Long's actor-centered approach, agency refers to the knowledge capacity, capability and social integration associated with acts of doing (and reflecting) that impact on or shape oneself and the actions and interpretations of others. Individuals or networks of individuals have agency and they can attribute agency to different objects and ideas which shape what actors see as possible. Agency is composed of a complex set of articulated social, cultural and material elements (Long, 2015a). In the attribution of agency to objects and ideas and the presence of material elements, the idea of actants explained in the previous section is taken up again. Long indicates that only actors are capable of putting actants into circulation. In this sense, agency implies the generation and use or manipulation of networks of social relations and the channeling of specific elements (such as demands, orders, goods, instruments and information) through nodal points of interpretation and interaction (Long, 2007).

It is also characterized by highlighting the main role of the individual as a social actor with the capacity to understand, interpret and question the macro-structures and dominant trends of Western development models –characterized by being exclusionary, authoritarian and, in general, designed in the bureaucratic spheres of the state, national and dominant elite –(Romero et al., 2012). Agency implies that social actors act according to their own interpretations of the situation and thus, assert their own normative values and goals, often through strategic actions (Landini et al., 2014a).

Recognizing that social actors have agency, social processes within AES are constituted by a series of psychosocial elements resulting from the relationships between the diversity of actors involved. This evidences local actors as active participants in development (not passive subjects). Agency helps to understand that the ways of doing and acting of local actors are based on their knowledge capacity (Long and Long, 1992). In other words, they make decisions according to their value preferences and the accumulation of available knowledge, resources and relationships. The farmer is seen as an active strategist who problematizes situations, processes information and gathers the necessary elements to act (Long, 2007). This main role shows how while interventions seek to assimilate their interests and practices, actors block, appropriate and assimilate them and in turn are mediated and transformed (Ye et al., 2009).

The intention of this work is to analyze psychosocial processes and this requires the inclusion of a psychological approach. This bridge between the social and psychological suggests an enriching and current approach to the recognition of social processes, material determinations, knowledge and technologies, all of which play a fundamental role in the context of rural development (Landini et al., 2014b). If agency goes beyond the local sphere, the complexity in these processes is recognized. Since the capacity for agency makes individuals try to solve problems and learn how to intervene in the flow of social events around them, they formulate and actively pursue their own development projects. Their plans may sometimes conflict with the interests of the people developing the external interventions or projects (Cieza and Vega, 2020).

An example that facilitates the understanding of agency is about the actors involved in the conservation of creole seeds. They have a list of factors that guide their choices and positions, which go beyond merely productive or external influences, and counteract the idea that socio-technical impositions reach all farmers homogeneously. Many farmers have biodiverse systems, i.e., agroecosystems in which the combination of social and organizational systems with productive systems of different species and varieties are important strategies to satisfy the different uses and needs of the families (Campos and Soglio, 2020).

This complexity in terms of a more or less rigid organization of elements and processes (both human and non-human) it is articulated at different levels and observable from different angles or scientific disciplines. It shows that these elements, processes or levels may be salient or more decisive in different situations or in regard to particular analyses, objectives or interests (Landini et al., 2014b). Considering that the AES are located in defined rural territories, it is useful to distinguish between these two types of contexts. The first is the spatial context which refers to extra-local or general (national or international) processes that have a discernible impact on the local processes under study, both at the psychosocial and non-psychosocial levels. The second is the non-psychosocial context which refers to non-psychosocial, local and extralocal factors (such as the economy, political structure and types of land tenure and agricultural technology) that have a psychosocial impact on our area of study. Therefore, this proposal places AES in the model of Agency and psychosocial processes in the context of the complexity proposed by Landini et al. (2014b) (**Figure 1**).

It is recognized that psychosocial processes are articulated with socio-political, economic, biophysical realities or levels of analysis and how they can be integrated or combined with the concepts of agency and strategies as indicated by Landini et al. (2014b). In this regard, the agroecosystem is situated as part of the complexity that encompasses the biophysical reality and the psychosocial processes where the local actors are situated. It is acknowledged that the agroecosystem is not restricted to this alone, but that the economic and socio-political levels of analysis cause a dynamic among the actors involved and that each exerts some degree of agency (**Figure 1**). They can include technological elements such as seeds, fertilizers, machinery, irrigation systems or symbolic elements implicit in credit and development programs, among others. Thus, it is important to understand the psychosocial processes in the agroecosystem in terms of social interfaces of multiple actors and non-human actors, which will allow for processes and power relations in the dynamics of interaction.

SOCIAL INTERFACES IN AGROECOSYSTEMS

There are interactions of a range of different actors, not only between the actors present in certain face-to-face encounters, but also among those absent who nevertheless influence the situation and thus affect actions and outcomes (Long, 2007). In this regard, Long points out that the *social interface* constitutes a node that makes it possible to analyze situations in an integrated manner in their heterogeneity and dynamism and to compare phenomena that are often thought of independently. It is a way to organize the study in a procedural sense to finally have a dynamic vision of all the social actors.

Therefore, this proposal considers that agroecosystems are the product of the interdependence of a diversity of actors; therefore, they constitute complex social interfaces. The social interface is conceptualized as.... "*a critical point of intersection between different lifeworlds, social fields or levels of social organization where social discontinuities, based on discrepancies in values, interests, knowledge and power, are most likely to be located*" (Long, 2007).

It also considers areas of knowledge and interaction that intertwine the perspectives of a great diversity of actors (state, non-governmental, the beneficiary population, providers of credit, technologies, machinery, tools and inputs). In other words, a field socially constructed on the basis of conflict and negotiation, in which the distribution of resources and the legitimization of the intervention processes of the different actors are defined (Feito, 2007). Pertaining to the above mentioned notion, social interfaces not only refers to whether perspectives, experiences and worldviews differ among the actors involved, but also how these encounters are shaped by unequal power relations, a now common approach in development cooperation (Gerharz, 2018).

Thus, the social interface is a conflictive space in which different frameworks of meaning are articulated and allows addressing the complex processes of appropriation, translation and reconfiguration of knowledge and recommendations that occur in this connection. It is relevant to consider that knowledge is a cognitive and social construction resulting from the experiences, encounters and discontinuities that arise at the points of intersection between the lifeworlds of different actors (interface). Then, the importance of interface analysis is to highlight the knowledge and power implications in this interaction and the mixing or segregation of opposing discourses (Landini et al., 2014b).

"*The concept of interface, is not simply there to represent the ability of 'structures' to functionally reproduce themselves or accommodate increasing incompatibilities, but to identify the potential of different actors to innovate and thus create the conditions for people and resources to realign themselves in different combinations*" (Long, 2015b). Interfaces are characterized by discontinuities in interests, values, power and their dynamics involving negotiation, accommodation and the struggle for definitions and boundaries (Long and Villarreal, 1993). According to the authors, a detailed study of interfaces provides important information on the processes by which: (a) policy is transformed, (b) how forms of power are generated, (c) how room for maneuver is created by both interveners and their beneficiaries, and (d) people are enmeshed within the projects of others through the use of development metaphors and images.

Social interfaces, however, extend beyond the rationalities of smallholder farmers to include the priorities and perspectives of various relevant development actors. Thus, they examine what happens when actors play different roles, have different identities, and exercise power in different ways (Tobin and Glenna, 2019). If the elements of the actor-centered perspective theory, agency and social interfaces are considered to understand the complexity of agroecosystems, it is necessary to deconstruct the elements located within the systemic approach in which the evolution of

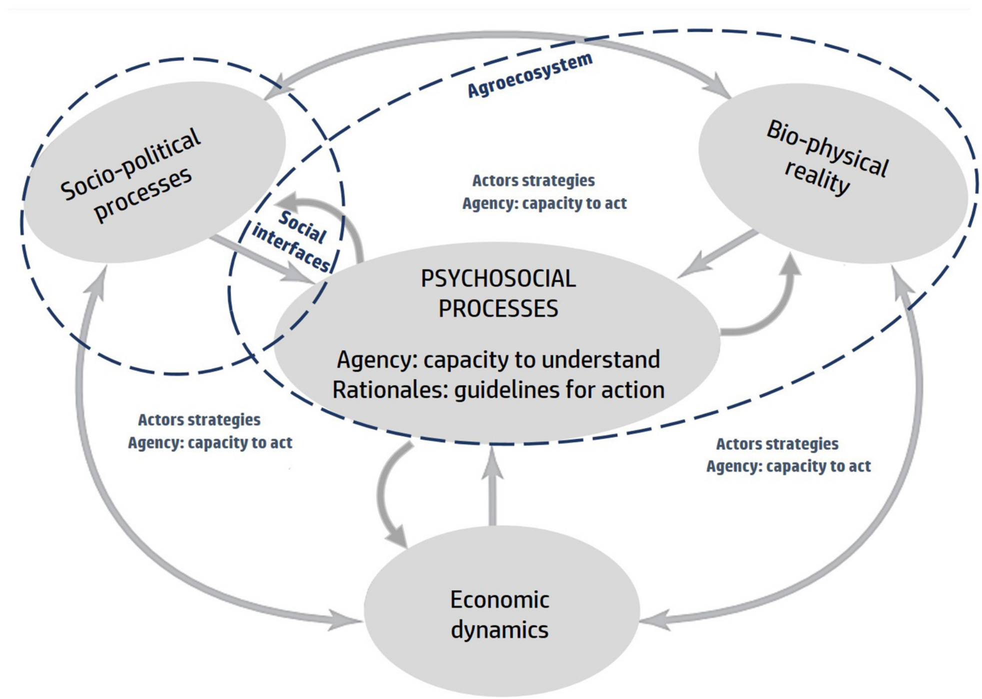

FIGURE 1 | Agency and psychosocial processes in the context of the complexity of agroecosystems (modified from Landini et al., 2014b).

the AES concept is framed. If these processes are recognized as dynamic, we must focus on the practices and daily life of the actors.

According to Long (2007), social actors should not appear as mere disembodied social categories (based on class or some other classificatory criterion) or passive recipients of interventions. Rather, they should be seen as active participants who receive and interpret information and design strategies in their relations with the various local actors, as well as with external institutions and their staff. These approaches are contrary to what has been worked on with respect to agroecosystems and the implications of the evolution of the concept in this work.

Mainly when considering farmers as passive subjects that receive external information to be able to make management decisions in their agroecosystem or considering them as categories to organize their social life (e.g., producers categorized as self-consumption, transition and commercial strata). Now, if we visualize in practice how the concepts of agency and social interface are articulated in the AES, we have that agency shows the actors' strategies and discursive encounters. Moreover, due to the actants, actors put into circulation, as mentioned above, interfaces which implies encounters between actors and between technologies and material resources.

Certainly, in agroecosystems, the social interface is an opportunity to no longer look only at static structural elements but at changes, adjustments and readjustments, which in practice means that in the AES:

1) Diverse local and external actors (not only farmers) interact, with agency capacity.
2) Social actors are active participants. They are not passive subjects in agroecosystems and development processes.
3) Social actors sometimes share common objectives but in many cases they are opposed to each other.
4) Interaction between actors are not simple relationships, they involve complex social interfaces, where different frameworks of meaning are articulated and complex processes of appropriation, translation and reconfiguration of knowledge can be understood.
5) They are constituted by complex social processes of interaction of a multiplicity of actors, so understanding farmers' practices requires a broader vision that considers macro-structures that impose agency at the local level, and e.g., the market, the state, planned development interventions.
6) Making the psychosocial elements visible helps to understand the relationships of the actors with their environment that affect and are affected by them.
7) Farmers' management decisions have to do not only with monetary values or production purposes, but also with implicit psychosocial elements that determine "why they do what they do."
8) The central elements in their social interfaces involve understanding the values, interests, knowledge and power of the actors involved.
9) It is relevant to consider the learning processes within the link between actors: farmers with technicians, policy designers and implementers, researchers, development agencies and a diversity of other actors.

10) Agricultural technologies, material resources and symbolic aspects implicit in development programs, credit -to mention a few- are actants that the actors put into circulation and form part of a set of interwoven agencies. These actants are transmitted by the actors and they are part of a set of intertwined agencies.

From these elements emerges the question: How can we visualize these elements within the AES? Methodologically, the following should be analyzed: farmers' practices, their encounters with technicians and extensionists, and the transactions (not only monetary) they carry out with marketers and collectors of their products. Besides, how they interact with the implementers of programs and projects planned by the State, organizations and institutions. At the same time, how the decisions of the State and the market exert political agency which is inserted in the daily life of local actors. All this represents, to a greater or lesser extent, the complexity of agroecosystems. Moreover, it should be emphasized that from this perspective, detailed ethnographic work is required to understand all these processes.

The ethnographic work "*aims to elucidate internally generated strategies and processes of change, the links between the small worlds of local actors and global phenomena and large-scale actors, and the decisive role played by diverse and often contradictory forms of human action and social consciousness in the making of development*" (Long, 2007). Ethnography, then, is a strategic process in which the researcher acts connecting experience and knowledge about the method with creativity and personal commitment. It is also a multitechnical strategy that achieves scientific rigor as it allows the emergence of the principles of creativity, systematicity, transparency and empirical reference (Nawrath, 2010). In consequence, we achieve a configuration of cultural contexts that takes into account the subjectivity, change and multilocal dynamics they hold and places us in a perspective that takes into account both the subjective and the social practices of the communities we investigate (Puentes, 2015).

DISCUSSION

From the actor-oriented approach, the social aspects of agroecosystems are not limited to farmers alone. But to a whole diversity of present and absent actors that operate in the social, cultural, political, economic, technological and environmental spheres. In addition, a series of aspects of social disorder rather than order are unraveled, showing the contradictions in social processes, as opposed to being interpreted as apathy in accordance with the dominant vision of progress that pretends to show a series of positive aspects and hegemonic character.

It is important to highlight that the predominant approach is oriented toward a problematic vision that evidences that the conception of agroecosystems is based on modern western rationality, centered on agriculture as a paradigmatic, manipulable and factory construct that considers the subject as an instrument that can create and manage it (Lugo Perea and Rodríguez Rodríguez, 2020), in other words, a Modern technical-scientific rationality that triggered the ecological and environmental crisis that encouraged its emergence (Sarandón, 2019). Even with these limitations, agroecological research and its object of study, agroecosystems, have now incorporated the social, economic, cultural and political factors that guide the path of the pluriepistemological character that is not very visible in the epistemological status of agroecology (Gallardo-López et al., 2019).

The challenge is still great, if we consider sustaining these visions from praxis. It seems that the guideline is to move toward the use of paradigms where the social actors, their development and the impacts of their social tasks in agriculture are considered the main axis (Gallardo-López et al., 2018). However, there are some important successes that consider agriculture as a social system that not only considers farmers, but also other actors that are related to them (Duru et al., 2015), the methodological scopes proposed by these authors focus on agricultural systems based on place and space, on the interactions between actors and on innovation processes that must be designed in a top-down manner. In this sense, we do not entirely agree, especially in the last aspect, since what we propose focuses on the actors and their capacity for agency, on relationships rather than interactions and on bottom-up processes that give protagonism to the actors in the local sphere. We clarify that we differentiate relationships from interactions because we recognize that agency requires the generation of relationships and guiding elements such as demands, goods, instruments and information through nodal points of interaction (Long and Villarreal, 1993). In this sense, the ten points we propose to address the social interfaces in agroecosystems are an opportunity that contributes to a new vision of agroecosystems from theory and practice.

CONCLUSIONS

This work shows that agroecosystems are the product of the interdependence of a diversity of actors (present and absent) and, therefore, constitute complex social interfaces, which require a new understanding of the centrality of the actors and their capacity for agency. The perspective centered on the actor, agency and the social interface was proposed as theoretical and conceptual tools to contribute to the understanding of these dynamic processes. They are principally related to psychosocial and relational processes in the context of the complexity of agroecosystems. Some initial considerations emerged from the analysis to visualize social interfaces in agroecosystems as well as some methodological guidelines which suggest a different approach to current approaches in the study of agroecosystems.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

FG-L, AL-G, and MH-C contributed to the design, analysis and writing of this manuscript. All authors contributed to the article and approved the submitted version.

REFERENCES

Altieri, M. (1999). *Agroecología: Bases Científicas Para una Agricultura Sustentable*. Editorial Nordan-Comunidad. Available online at: http://www.fao.org/agroecology/database/detail/es/c/893011/

Altieri, M. A., and Nicholls, C. I. (2020). Agroecology and the reconstruction of a post-COVID-19 agriculture. *J. Peasant Stud.* 47, 881–898. doi: 10.1080/03066150.2020.1782891

Campos, M. L. D., and Soglio, F. K. D. (2020). Creole seeds and power relations in agriculture: interfaces between biopower and social agency. *Amb. Soc.* 23:e02422. doi: 10.1590/1809-4422asoc20180242r2vu2020l5ao

Casanova, L., Martínez, J., López, S., and López, G. (2016). De von Bertalanffy a Luhmann: deconstrucción del concepto "agroecosistema" a través de las generaciones sistémicas. *Rev. Mad* 35, 60–74. doi: 10.5354/0718-0527.2016.42797

Casanova-Pérez, L., Martínez-Dávila, J. P., López-Ortiz, S., Landeros-Sánchez, C., López-Romero, G., and Peña-Olvera, B. (2015). El agroecosistema comprendido desde la teoría de sistemas sociales autopoiéticos. *Rev. Mex. Cien. Agríc.* 6, 855–865. doi: 10.29312/remexca.v6i4.625

Chandra, A. (2017). The relevance of political ecology perspectives for smallholder climate-smart agriculture. *J. Political Ecol.* 24, 821–842. doi: 10.2458/v24i1.20969

Cieza, R. I., and Vega, M. (2020). El programa cambio rural en el periurbano platense: un estudio desde la perspectiva de los actores (2009-2017). *Estudios Rural.* 10, 1–18. Available online at: http://portal.amelica.org/ameli/jatsRepo/181/181929033/index.html

Cittadini, R. A., and Pérez, R. (1996). La importancia de comenzar entendiendo por que el productor hace lo que hace. el caso de maíz para forraje. *Vis. Rural* 5, 36–39.

Cruz-Bautista, P., Casanova-Pérez, L., Martinez-Davila, J. P., Flores-Martinez, C., and Villegas-Rodriguez, I. (2019). Family as a social system and homegarden agroecosystem: conceptual theoretical model from the Luhmannian theory [agriculture; Luhmann; first order observer; second order observer; social-environmental phenomena.]. *Trop. Subtrop. Agroecosyst.* 22, 713–722. Available online at: http://www.revista.ccba.uady.mx/urn:ISSN:1870-0462-tsaes.v22i3.2906

Duru, M., Therond, O., and Fares, M., h. (2015). Designing agroecological transitions; a review. *Agron. Sustain. Dev.* 35, 1237–1257. doi: 10.1007/s13593-015-0318-x

Feito, M. C. (2007). Modalidades de intervencion social sobre los horticultores bonaerenses: una mirada antropologica. *Avá* 19, 78–96. Available online at: http://ref.scielo.org/b6nwmr

Fernández González, C., Ollivier, G., and Bellon, S. (2020). Transdisciplinarity in agroecology: practices and perspectives in Europe. *Agroecol. Sustain. Food Syst.* 45, 523–550. doi: 10.1080/21683565.2020.1842285

Gallardo López, F. *Los agroecosistemas de la Subprovincia Llanura Costera Veracruzana: Una propuesta para la caracterización y el análisis tipológico de la agricultura regional Campus Veracruz.* Veracruz: Colegio de Postgraduados (2002).

Gallardo-López, F., Hernández-Chontal, M. A., Cisneros-Saguilán, P., and Linares-Gabriel, A. (2018). Development of the concept of agroecology in europe: a review. *Sustainability* 10:1210. doi: 10.3390/su10041210

Gallardo-López, F., Hernández-Chontal, M. A., Linares-Gabriel, A., and Cisneros-Saguilán, P. (2019). Scientific contributions of agroecology in Latin America and the Caribbean: a review. *Rev. Facul. Cien. Agr.* 51, 215–229. Available online at: https://revistas.uncu.edu.ar/ojs3/index.php/RFCA/article/view/2447

Gallardo-López, F., Hernández-Chontal, M. A., Linares-Gabriel, A., and Cisneros-Saguilán, P. (2020). The postgraduate course in tropical agroecosystems: facing the challenges for Mexican agriculture in the 21st century. *Agro Prod.* 13, 53–60. doi: 10.32854/agrop.v13i11.1812

Gerharz, E. (2018). *The Interface Approach (3927276987). I. W. Papers*. Available online at: https://www.econstor.eu/handle/10419/183566

Giddens, A. (2011). *La Constitución de la Sociedad: Bases para la Teoría de la Estructuración, 2nd Edn*. México: Amorrortu.

Gliessman, S. (2011). Transforming food systems to sustainability with agroecology. *J. Sustain. Agric.* 35, 823–825. doi: 10.1080/10440046.2011.611585

Gliessman, S. (2012). Redesigning agroecosystems. *J. Sust. Agric.* 36, 381–381. doi: 10.1080/10440046.2012.662583

Gliessman, S., and Ferguson, B. G. (2021). An urgent call for deep food system change. *Agroecol. Sustain. Food Syst.* 45, 1–2. doi: 10.1080/21683565.2020.1831731

Hebinck, P., den Ouden, J., and Verschoor, G. (2001). "Past, present and future: long's actor-oriented approach at the interface," in *Resonances and Dissonances in Development: Actors, Networks and Cultural Repertoires*, eds P. Hebinck, G. Verschoor, N. Long (Assen: Royal van Gorcum), 1–16.

Hendrickson, J. R., Hanson, J. D., Tanaka, D. L., and Sassenrath, G. (2008). Principles of integrated agricultural systems: introduction to processes and definition. *Renew. Agric. Food Syst.* 23, 265–271. doi: 10.1017/S1742170507001718

Josol, M. R. C., and Montefrio, M. J. F. (2013). Understanding the resilience of Swidden agroecosystems interacting with rubber and oil palm production regimes in the Philippines. *Agroecol. Sustain. Food Syst.* 37, 812–833. doi: 10.1080/21683565.2013.775540

Landini, F., Cowes, V. G., and Damore, E. (2014a). Hacia un marco conceptual para repensar la accesibilidad cultural. *Cadern. Saúde Púb.* 30, 231–244. doi: 10.1590/0102-311X00030313

Landini, F., Leeuwis, C., Long, N., and Murtagh, S. (2014b). Towards a psychology of rural development processes and interventions. *J. Commun. Appl. Soc. Psychol.* 24, 534–546. doi: 10.1002/casp.2187

Larrión, J. (2019). Teoría del actor-red. Síntesis y evaluación de la deriva postsocial de Bruno Latour. *Rev. Españ. Sociol.* 28, 323–341. doi: 10.22325/fes/res.2019.03

Latour, B. (1996). Do scientific objects have a history? Pasteur and Whitehead in a bath of lactic acid. *Common Knowl.* 5, 76–91.

Leeuwis, C., Long, N., and Villarreal, M. (1990). Equivocations on knowledge systems theory: an actor-oriented critique. *Knowl. Technol. Policy* 3, 19–27.

Long, N. (1990). From paradigm lost to paradigm regained? The case for an actor-oriented sociology of development. *Eur. Rev. Latin Am. Caribbean Stud.* 49, 3–24.

Long, N. (2001). "The case for an actor-oriented sociology of development," in *Development Sociology: Actor Perspectives, 1st Edn*, ed N. Long (Routledge: Taylor & Francis e-Library), 1–7.

Long, N. (2007). *Sociología del Desarrollo: Una Perspectiva Centrada en el Actor*. Transl. by M. V. y. P. R. Horacia Fajardo. Centro de Investigaciones y Estudíos Superiores an Antropología Social (CIESAS) y el Colegio de San Luis (COLSAN), México.

Long, N. (2015a). "Acercando las fronteras entre la antropología y la psicología para comprender las dinámicas de desarrollo rural," in *Hacia una Psicología Rural Latinoamericana*, eds F. L. (Coordinador) (Buenos Aires: CLACSO Consejo Latinoamericano de Ciencias Sociales), 77–96.

Long, N. (2015b). "Activities, actants and actors: theoretical perspectives on development practice and practitioners," in *Constructing a New Framework for Rural Development,* eds Milone, P. Ventura, F., and Ye, J. Vol. 22 (Bingley: Emerald Group Publishing Limited), 31–58.

Long, N., and Liu, J. (2009). The centrality of actors and interfaces in the understanding of new ruralities: a Chinese case study. *J. Curr. Chin. Affairs* 38, 63–84. doi: 10.1177/186810260903800404

Long, N., and Long, A. (1992). *Battlefields of Knowledge: The Interlocking of Theory and Practice in Social Research and Development*. Routledge: Taylor & Francis Group.

Long, N., and Villarreal, M. (1993). "Exploring development interfaces: from the transfer of knowledge to the transformation of meaning," in *Beyond the Impasse: New Directions in Development Theory*, ed F. J. Schuurman, 140–168. Available online at: https://www.scopus.com/inward/record.uri?eid=2-s2.0-0027796117&partnerID=40&md5=b1c8f29bb57ea58cdf3da198dcd34c7b

Lugo Perea, L. J., and Rodríguez Rodríguez, L. H. (2020). *Perturbando el Texto Agroecológico: Anotaciones para una (Urgente) Des-Colonización de la Agroecología Ibagué: Colectivo de Pensamiento Agroecológico*. Ibagué: Sello Editorial Universidad del Tolima.

Martínez, R. (2004). Fundamentos culturales, sociales y económicos de la agroecología. *Rev. Cien. Soc.* 1–2. Available online at: https://www.redalyc.org/articulo.oa?id=15310407

Mason, R. E., White, A., Bucini, G., Anderzén, J., Méndez, V. E., and Merrill, S. C. (2020). The evolving landscape of agroecological research. *Agroecol Sustain Food Syst.* 45, 1–41. doi: 10.1080/21683565.2020.1845275

Nawrath, H. I. M. (2010). *El Método Etnográfico: Origen y Fundamentos de una Aproximación Multitécnica*. Forum Qualitative Sozialforschung/Forum: Qualitative Social Research, 11: 1–31. https://hdl.handle.net/10925/618

Puentes, J. A. (2015). La hermenéutica como anclaje epistémico del método etnográfico. *Vivat Acad.* 1–11. doi: 10.15178/va.2015.133.1-11

Roldán-Rueda, H. N. (2020). El rol de los actores en mercados locales y campesinos de México y Colombia. *Estudios Soc. Rev. Aliment. Contemp. Desarrollo Regional* 30, 1–30. doi: 10.24836/es.v30i56.1029

Romero, Y. H., Ramos, G. A., and Muñoz, J. P. (2012). Análisis y configuración del desarrollo regional. Un enfoque desde los actores. *Espacios Públ.* 15, 188–207. Available online at: http://hdl.handle.net/20.500.11799/39741

Sarandón, S. (2014). "El agroecosistema: un ecosistema modificado," in *Agroecología: bases teóricas para el diseño y manejo de agroecosistemas sustentables*, eds S. Sarandón, and C. y Flores (Buenos Aires: Editorial de la Universidad de La Plata), 100–130.

Sarandón, S. J. (2019). Potencialidades, desafíos y limitaciones de la investigación agroecológica como un nuevo paradigma en las ciencias agrarias. *Rev. Facult. Cien. Agrar. UNCuyo* 51, 383–394. Available online at: https://revistas.uncu.edu.ar/ojs3/index.php/RFCA/article/view/2458

Sarker, M. N. I. (2017). An introduction to agricultural anthropology: pathway to sustainable agriculture. *J. Sociol. Anthropol.* 1, 47–52. doi: 10.12691/jsa-1-1-7

Sicard, T. E. L. (2009). Agroecología: desafíos de una ciencia en construcción. *Agroecología* 4, 7–17. Available online at: https://revistas.um.es/agroecologia/article/view/117121

Tittonell, P. (2019). Las transiciones agroecológicas: múltiples escalas, niveles y desafíos. *Rev. Facult. Cien. Agrar. UNCuyo* 51, 231–246. Available online at: https://revistas.uncu.edu.ar/ojs3/index.php/RFCA/article/view/2448

Tittonell, P., Piñeiro, G., Garibaldi, L. A., Dogliotti, S., Olff, H., and Jobbagy, E. G. (2020). Agroecology in large scale farming—a research agenda. *Front. Sustain. Food Systems* 4:584605. doi: 10.3389/fsufs.2020.584605

Tobin, D., and Glenna, L. (2019). Value chain development and the agrarian question: actor perspectives on native potato production in the highlands of Peru. *Rural Sociol.* 84, 541–568. doi: 10.1111/ruso.12251

Turner, S. (2012). Making a living the hmong way: an actor-oriented livelihoods approach to everyday politics and resistance in upland Vietnam. *Ann. Assoc. Am. Geogr.* 102, 403–422. doi: 10.1080/00045608.2011.596392

Ye, J., Wang, Y., and Long, N. (2009). Farmer initiatives and livelihood diversification: from the collective to a market economy in Rural China. *J. Agrarian Change* 9, 175–203. doi: 10.1111/j.1471-0366.2009.00191.x

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SYSTEMATIC REVIEW
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Agroecological Transitions: A Systematic Review of Research Approaches and Prospects for Participatory Action Methods

Erwan Sachet[1,2], Ole Mertz[1], Jean-François Le Coq[2,3,4], Gisella S. Cruz-Garcia[5], Wendy Francesconi[2], Muriel Bonin[6] and Marcela Quintero[2]*

[1] Section for Geography, Department of Geosciences and Natural Resource Management, University of Copenhagen, Copenhagen, Denmark, [2] Multifunctional Landscapes, The International Center for Tropical Agriculture (CIAT), Cali, Colombia, [3] The French Agricultural Research Center for International Development (CIRAD), UMR ART-DEV, Montpellier, France, [4] Consortium of International Agricultural Research Centers (CGIAR) Research Program on Climate Change, Agriculture and Food Security (CCAFS), Wageningen, Netherlands, [5] Oxfam Novib, The Hague, Netherlands, [6] The French Agricultural Research Center for International Development (CIRAD), UMR TETIS, Montpellier, France

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***Correspondence:**
Erwan Sachet
egns@ign.ku.dk

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There have been many calls for an agroecological transition to respond to food shocks and crises stemming from conventional food systems. Participatory action research and transformative epistemologies, where communities are research actors rather than objects, have been proposed as a way to enhance this transition. However, despite numerous case studies, there is presently no overview of how participatory approaches contribute to agroecological transitions. The present article therefore aims to understand the effect of applying participatory action research (PAR) in agroecology. We undertook a systematic review of articles reporting methods and results from case studies in agroecological research. On the one hand, our systematic review of 347 articles shows that the agroecological research scope is broad, with all three types—as science, a set of practices and social movement—well-represented in the corpus. However, we can see a clear focus on agroecology "as a set of practices" as the primary type of use of the concept. On the other hand, we found a few case studies (23) with a participatory approach while most studies used extractive research methods. These studies show that understanding the drivers and obstacles for achieving an agroecological transition requires long-term research and trust between researchers and farmers. Such transformative epistemologies open doors to new questions on designing long-term PAR research in agroecology when confronted with a short-term project-based society.

Keywords: systematic review, participatory action research, agroecology, transition, epistemic perspective

INTRODUCTION

For some decades, agroecology has been presented as a reliable alternative to conventional agriculture, even though the definitions vary significantly (Stassart et al., 2012). Agroecology is often seen as either a relatively standardized biophysical climate-soil-landscape framework that may benefit long-term agricultural production (FAO., 1996; Fischer et al., 2005) or a much broader approach to achieving sustainable food systems through ecological principles (Altieri, 1989; Francis et al., 2003; Gliessman, 2015). In other words, the term agroecology, which appeared primarily as a natural science field at the start of the 20th century, had its scope widened. Wezel et al. (2009) advocated that agroecology comprises three interlinked and complementary approaches: agroecology "as a scientific discipline," "as a set of practices," and "as a movement."

Thus, the scale at which agroecology was being studied broadened from plots and fields to food systems and regimes, the latter intertwined with food sovereignty movements (Wezel and Jauneau, 2011; McMichael, 2014). More recently, the debate has centered on the politics of the agroecological transition and food system transformation versus agricultural conformism (Rosset and Altieri, 2017; Giraldo and Rosset, 2018). Indeed, food is at the center of social-political stability, and agroecology might provide resilience toward food shocks and crises (De Schutter, 2010; De Schutter and Vanloqueren, 2011; Pimbert, 2017; Rosset and Altieri, 2017).

Henceforth, research and discussion on agroecology have been enriched by questioning its scalability. Although several works have demonstrated the potential of agroecology as "truly sustainable" (Altieri and Nicholls, 2005; De Schutter, 2010; HLPE., 2019, Chapter 1), agroecology has still been to a lesser extent integrated into current agricultural public policy agendas (Migliorini and Wezel, 2017). Non-government organizations (NGOs) and academics promote agroecology in various international arenas such as FAO's Agroecological hub and the Scientific Society of Agroecology (SOCLA), but according to La Vía Campesina. (2018) efforts to develop public policies supporting peasant agroecology are still scarce. For this reason, some organizations and academics demand a radical change in the food research agenda and project funding: democratizing the research and steering agricultural extension funds to agroecological programs must be the foremost strategy to achieve the agroecological transition (Fernández, 2006; Pimbert, 2017; Barling et al., 2018).

To some extent, the FAO and the European Union have included aspects of agroecology in recent official agendas (European Union., 2017; FAO., 2018a). However, while there is some level of support for disseminating and scaling up agroecology at the country level, there is no consensus on achieving it. For example, within their distinct socio-historical contexts, several Latin American countries have dealt with agroecology at the policy level in various ways based on their visions of what constitutes (or not) agroecology (Sabourin et al., 2017). On the one hand, some call for the complete transformation of food systems, coined by the term "transformative agroecology." On the other hand, some call for a "conformist agroecology," which includes a portfolio of practices that congregate with other concepts, such as conservation agriculture and climate-smart agriculture (Pimbert, 2017; Giraldo and Rosset, 2018). Giraldo and Rosset (2018) mentioned that agroecology's multiple dimensions and definitions are the root causes of these divergences.

Agroecological approaches to food systems explain the dichotomy between transformative and conformist agroecology (**Table 1**). Conformist agroecology emphasizes the food security rationale and proposes agroecological practices as an add-on to the portfolio of "sustainable" practices, such as climate-smart agriculture or "ecological" intensification. From another perspective, transformative agroecology focuses not only on food sovereignty but also on food and nutrition security and promotes agroecology as an interconnection between science, practice, and social movements. In other words, agroecology is not solely a set of sustainable practices but a merging of approaches (science, practices, and movements) to achieve sustainable, equitable, and just food systems, while respecting ecological principles. Thereby, research on transformative agroecology would involve anthropological methods (e.g., to assess local knowledge, practices, and cultural values, and identify community priorities as part of bottom-up approaches), alongside the application of multiple scientific disciplines that encourage interdisciplinary methodologies.

Transformative agroecology requires a fundamental shift in knowledge production. Hence, researchers in agroecology should reorient methods supporting research results constructed through specific social contexts (Levidow et al., 2014). Such a positional shift means the inclusion of methodologies that promote the active participation of non-academic people in the research process. Participatory action research (PAR) facilitates such research co-design and activities through scientist-farmer alliances (Armitage et al., 2009; Bohensky and Maru, 2011; Huntington, 2011; Mauser et al., 2013) and has been discussed among the agroecological community (Fernández, 2006; Altieri and Toledo, 2011; Duru et al., 2015; Pimbert, 2017). It proposes mixed and pluralistic methods to improve understanding of the complexities associated with the transformation of agri-food systems (Chambers, 2015) and includes participatory methods in research cycles, which enable the assimilation of research design and outcomes by non-academics.

The rationales of PAR and transformative agroecology are closely related. The primary idea is to avoid the linear research typical in many research and development (R&D) projects in agriculture, in which the end process is knowledge/technology transfer (Levidow et al., 2014). Instead, PAR proposes a framework based on research cycles, in which communities are no longer a research object but become a research actor (Kindon et al., 2007a). Their participation in research aims at enhancing their self-determination and autonomy over the process (Kindon et al., 2007b; Fals Borda, 2013) by defining, in collaboration with the researchers, the research problem and the research design, and evaluating the outcomes expected. Framing research in such a way requires a highly sensitive and adaptive methodology and a philosophical/epistemological position that goes beyond classical agricultural science (Kesby et al., 2007; Kindon et al., 2007a; Fals Borda, 2013; Chambers, 2015). As Levidow et al. (2014) argue, democratizing research and increasing funds for PAR and agroecological research are needed, along with research design for autonomous learning and action.

PAR has been applied for agroecological implementation. For instance, Guzmán et al. (2012) demonstrated the rationale and the *praxis* of using a PAR framework to build local food webs in Spain. The experience exemplifies how to conduct

TABLE 1 | The dichotomy of agroecology worldviews (based on and adapted from Levidow et al., 2014; Giraldo and Rosset, 2018).

	Transformative agroecology	Conformist agroecology
Vision	Agroecology is the alternative to industrial agriculture and is part of the struggle to challenge and transform monoculture, input dependency, and existing power structures. Facing the problem and vulnerability of conventional agriculture, it looks to transform the food system.	Agroecology offers tools to fine-tune industrial agriculture and conform to monoculture, input dependency, and power structures. It looks for adaptation to the problem created by conventional agriculture.
Approach to food	Food sovereignty and security	Food security
Agroecology as...	An interconnection of science, a set of practices, and social movements	A portfolio of sustainable practices
Disciplinary	Interdisciplinary/transdisciplinary of social, anthropological, and natural sciences	Multidisciplinary of natural sciences (based on agronomic sciences)
Social sciences scope	Promotes the use of critical and interdisciplinary methodologies and participatory action research (PAR)	Promotes the use of a rapid rural appraisal (RRA) and participatory rural appraisal (PRA) for contextualization
Main actors	Social movements, civil society organizations, and scientific councils such as *via* Campesina, SOCLA, and Landless Workers' Movement (MST)	Institutions such as the FAO, World Bank, CGIAR, and government bodies

PAR for agroecology with smallholders and presents a complete design of research phases with appropriate methods and participation levels. In a comparative study, Méndez et al. (2017) analyzed the lessons learned from two case studies integrating PAR and agroecology principles. They concluded that this methodological approach was essential for building long-term benefits of implementation *via* organized, constant, and trustworthy relations between researchers and the community.

Recent studies show the variety of PAR methods and instruments used for agroecological implementation. For instance, PAR opens space for role-playing games in multi-stakeholder arrangements to develop agroforestry landscapes supporting a collective plan for sustainable landscapes (Andreotti et al., 2020). Another example shows that a participatory guarantee system can support the agroecological transition in a local market network *via* PAR methods and principles (Chaparro-Africano and Naranjo, 2020). Thus, transformative methodologies, such as PAR, seem to be key to accomplishing the agroecological transition, particularly if it is to be upscaled. However, despite various case studies, there is no overview of how PAR has been included in agroecological research and the role PAR plays for the agroecological transition

This article provides a systematic review to understand to what extent PAR is prevalent in transformative agroecology, and which of the different PAR epistemic approaches contribute to the agroecological transition.

METHODS

We searched two scientific abstract and citation databases to identify articles that describe agroecology case studies: Scopus® and Web of Science™. These databases were chosen as they include only peer-reviewed research and allow for systematic searches. We considered using other databases (CAIRN, Dialnet, DOAJ, HAL, Latindex, Redalyc, Scielo) to find more local case studies, but these were discarded as they included neither advanced research tool nor Boolean values (nor both) that allow systematic queries.

The query terms used were agroecolog* and case* stud*. The use of the wildcard "*" allowed including several wordings for each term. For the term agroecology, we employed three possible ways of writing it that may appear in the literature: agroecolog*, agro-ecolog*, and agro*ecolog*, separated by the Boolean operator "OR." As the research query with sole agroecology resulted in many records (8313 in Scopus® and 6441 in Web of Science™), the choice of adding "case study" as a keyword was justified considering a systematic review. As Yin (2009) underline, case studies are an inclusive research design and permit various (mixed-) research methods. As such, the choice of using "case study" as keywords allowed us to have a representative sample of agroecological implementation research and methods used. In Scopus®, we typed query terms in the *Title–Abstract–Keyword* search field. In Web of Science™, the terms were typed in the *Topic* search field, equivalent to the search field *Title-Abstract-Keyword* in Scopus®. We selected articles published until the 31st of December 2018. The queries in the two abstract and citation databases yielded 856 records.

We used the PRISMA statement to constitute the article database (Liberati et al., 2009; Moher et al., 2009). We conducted four filtering phases: identification, screening, eligibility, and inclusion (**Figure 1**). The screening consisted of an overview of the article's metadata, such as titles, type of documents, subject area, and authors. This phase helped us to ensure the first filtering of the database by removing duplicates ($n = 246$), records that did not meet peer-reviewed journal article standards (introduction, methods, results, discussion, conclusion; book chapters mainly, $n = 45$), records without any of the search terms in their title, abstract and keywords ($n = 32$) and records that were not in English, French, or Spanish ($n = 31$). As a result, we selected 502 records for the subsequent phases.

The eligibility phase consisted of scrutinizing various article features to include the most relevant articles for the in-depth analysis. We filtered records that were not case studies ($n = 40$), not about agroecology ($n = 62$), not accessible ($n = 6$), and ones that were secondary case studies (i.e., relying exclusively on secondary data or reviewing case studies, $n = 45$).

It resulted in 347 articles to analyze primarily through a screening (see **Table 2** and **Supplementary Table S1**). The articles referring to agroecology as agro-ecological zoning (AEZ) were included solely in the screening analysis (Database 1). AEZ

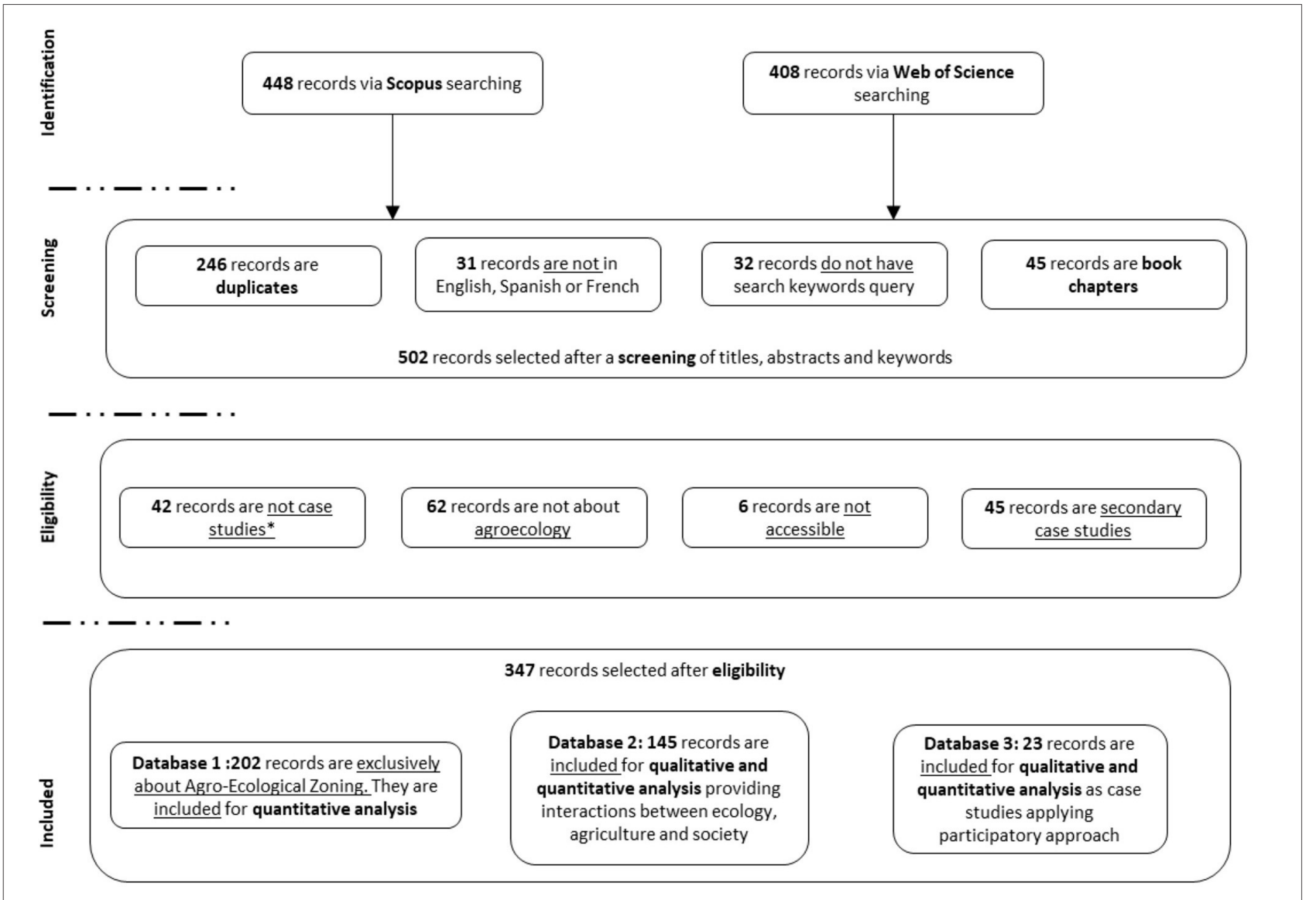

FIGURE 1 | PRISMA statement process undertaken for the selection of relevant articles. *22 records were annotated outlines; three records were literature reviews; two records were conceptual framework; two records were discussion paper; two records were editorial material; two records were about modeling without CS; one record was a forum paper; one record was a commentary; one record was a conference session summary; one record was a communication; one record was a dataset paper; one record was a Ph.D. thesis; one record was a review paper; one record was a synthesis; one record was a systematic review protocol.

defines an area's edaphic and climatic conditions for agricultural development purposes but does not provide any information about the interaction between agriculture and the broader socio-ecological food system. As such, most of the articles referring to AEZ do not use the meanings underlined by Wezel et al. (2009) but attribute the study area's characteristics through AEZ principles (see FAO., 1996).

The remaining articles were first analyzed by assessing the study area (continent, country, and region), the study's scale, and the academic disciplines involved. We mainly screened the titles, abstracts, and keywords to obtain information about these variables and coded articles in the database accordingly.

In a second step, we examined a set of articles ($n = 145$, Database 2) by screening the articles to highlight and code articles consistently with agroecological features, such as the type of agroecology (as a science, as a set of practices, as a movement) and the scale of agroecology (plot/field scale, agroecosystem, food system, food regime). Based on Giraldo and Rosset (2018), we also classified and coded the articles according to agroecological positioning, that is, their viewpoint on the agroecological transition (conformist or transformative).

The final step consisted of an in-depth analysis of case studies employing participatory methods ($n = 23$, Database 3, cells shaded in gray in **Supplementary Table S1**). By thoroughly reviewing the articles, we deepened the analysis on agroecological positioning and the participatory methods (i.e., inclusion of PAR or different methods), the rationale behind the method, and the epistemic perspective that the articles are engaging with. We mainly used Excel and R basic package for the descriptive analysis, chi-square analysis, and tables.

RESULTS AND ANALYSIS

Position on Agroecology in the Corpus

From all case studies selected ($n = 347$, see **Table 3**), 60% referred to agroecology as agro-ecological zoning, of which 202 articles were exclusively about AEZ (58%). A fair share of case studies focuses on agroecology as a set of practices (27% of overall; 64% of the articles without referring to AEZ). The proportion of

TABLE 2 | The analytical framework for analyzing extracted articles.

Analytical framework	Analysis based on abstract screening			Analysis based on article screening			In-depth analysis			
	Case study localization	***The scale of the study***	***The scientific disciplines called in***	***Type of agroecology***	***Scale of agroecology***	***Position on agroecology***	***Methods***	***Type of data collection***	***Methods***	***Epistemic perspective***
Database 1: Articles solely on AEZ (*n* = 202)	X	X	X							
Database 2: Articles providing interactions between agriculture, ecology, and society (*n* = 145)	X	X	X	X	X	X				
Database 3: Articles including case studies using a participatory approach (*n* = 23)	X	X	X	X	X	X	X	X	X	X

TABLE 3 | Type of agroecology referred to in the selected case studies.

Type of agroecology	**Number of case studies (*n* = 347)**
Agro-ecological zoning (AEZ)	209
As a science	46
As a set of practices	95
As a movement	44
Exclusive	
Exclusively AEZ	202
Exclusively as a science	25
Exclusively as a set of practices	50
Exclusively as a movement	24
Combined	
AEZ + As a science	1
AEZ + As a set of practices	6
As a science + As a set of practices	19
As a set of practices + As a movement	19
As a science + As a set of practices + As a movement	1

articles referring to agroecology as a science or as a movement was similar.

When crossing agroecological type and geographical location, case studies in Africa and Asia focus mainly on AEZ, that is, landscape zoning *via* agroclimatic conditions (**Figures 2**, **3** and **Supplementary Figure S1**). In comparison, case studies in the Americas and Europe, agroecology as a set of practices prevails. Hence, 22% of the articles ($n = 21/95$) conceptualize agroecology as a set of practices in South America and 13% in North America ($n = 12/95$). In South America, we found 45% of the articles addressing agroecology as a movement, with 60% of those in Brazil (**Supplementary Figure S2**).

In the corpus, the scale of the case study related significantly to the agroecological type (**Figure 4**). For example, most case studies referring to agroecology as a science focus on issues at the field/plot level (agronomic trials, biological surveys, and laboratory analyses). In contrast, case studies referring to agroecology as a movement focus on a larger scale, such as the food system (78%). Agroecology as a set of practices is studied at all scales; nevertheless, most of those case studies (70%) focus on either agroecosystem (33%) or the food system (37%).

The in-depth analysis shows more comprehensive positions that deepen agroecology's triptych as a science, a set of practices, or a movement. Above all, the primary justification for agroecology as a set of practices is that agroecology is a path for sustainable development (Holt-Giménez, 2002; Cools et al., 2003; Bergquist et al., 2012; Lanka et al., 2017; Ryschawy et al., 2017; Simon et al., 2017; van Niekerk and Wynberg, 2017; Stein et al., 2018; Bezerra et al., 2019). The rationale focuses on the diversification of techniques (praxis and technologies) that protect and respect local ecosystems, biodiversity, and ecologies (Holt-Giménez, 2002; Cools et al., 2003; Ryschawy et al., 2017; Simon et al., 2017; van Niekerk and Wynberg, 2017), but also the diversification of healthy food production (Bergquist et al., 2012; Stein et al., 2018). Furthermore, agroecological practices, *via* the ecological services generated, are shown to improve resilience to environmental degradation and climate change (Holt-Giménez, 2002; Rogé et al., 2014). Thus, agroecological practices are argued to improve sustainable livelihoods by restoring ecosystems and improving ecological services in agroecosystems (Lanka et al., 2017; Simon et al., 2017).

Besides studies demonstrating that agroecological practices improve sustainable livelihood *via* the preservation and use of ecological services and functions, other studies connect the different types of agroecology. Then, perspectives of agroecological praxis go beyond the portfolio of practices for sustainable agriculture. Practicing agroecology triggers new approaches to the food system *via* the design of the agroecosystem (Rogé et al., 2014; Ryschawy et al., 2017; Prost

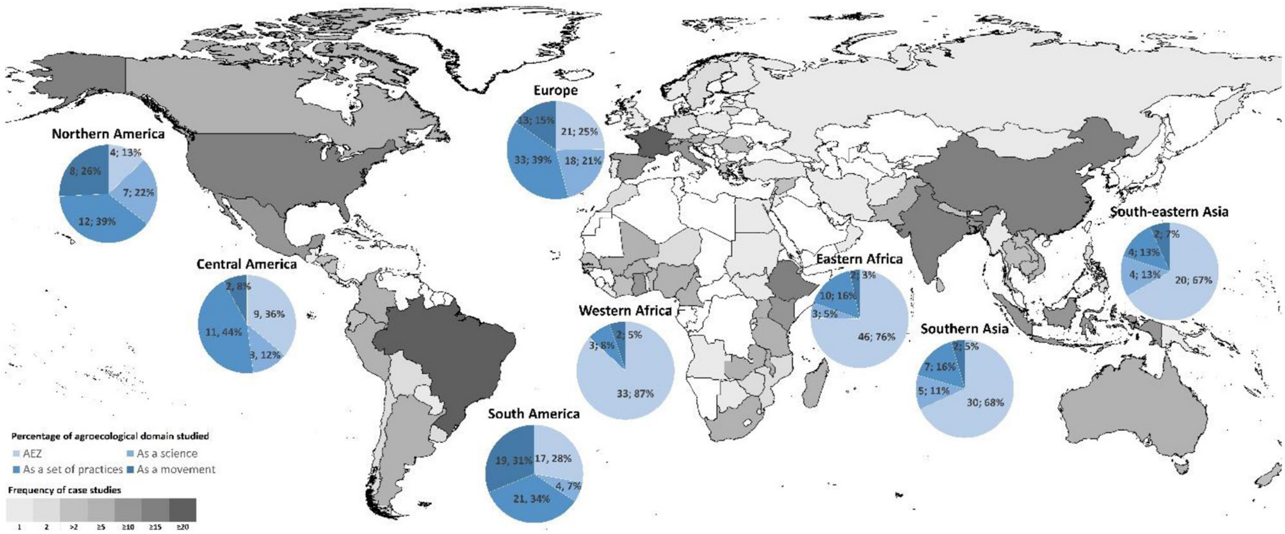

FIGURE 2 | Regional location of case studies and the percentage of the agroecological type studied in each region. Distribution: North America (*n* = 23); Central America (*n* = 20); South America (*n* = 52); Europe (*n* = 68); Western Africa (*n* = 37); Eastern Africa (*n* = 54); Southern Asia (*n* = 42); South-eastern Asia (*n* = 27).

	AEZ	As a science	As a set of practices	As a movement
Africa	89	4	12	3
Americas	31	14	44	27
Asia	66	12	15	4
Europe	21	18	33	13
Oceania	8		2	2

FIGURE 3 | Distribution of case studies according to the agroecological type and continental location. In the column heading, the gray bar represents the frequency of case studies on the continents. In the row label, the gray bar represents the frequency of case studies referring to agroecological type. Circles are proportional to the frequency of cases.

et al., 2018; Stein et al., 2018). This scope widens when practices reinforce cooperation between farmers, thus institutionalizing agroecological programs and strengthening community and family networks (Acevedo-Osorio et al., 2017; Lanka et al., 2017). Thus, agroecological practices become intertwined with social movements (or agroecology as a movement) through education and collective action (Guzmán et al., 2012; Rogé et al., 2014; Acevedo-Osorio et al., 2017; Bezerra et al., 2019).

Parallel to authors focusing on agroecological practices, the reviewed papers also indicated that agroecology as a movement supports sustainable agriculture (Holt-Giménez, 2002; Isgren and Ness, 2017; Stein et al., 2018). This line of thought considers that agroecology should empower farmers by realizing their influence in the food system (Tran, 2013; Rogé et al., 2014; Stein et al., 2018) and taking a significant part in food system decision making (Tran, 2013; Apgar et al., 2017; Misra, 2018). Agroecology is thus a movement that empowers small-scale farmers by increasing communitarian cooperation and subsequent autonomy (Holt-Giménez, 2002; Isgren and Ness, 2017; Lanka et al., 2017; van Niekerk and Wynberg, 2017). Thanks to such social empowerment, some authors suggest that agroecology diverges from conventional agriculture and "technocratic farming" (which focuses on food commoditization), and draws attention to structural problems in agriculture: input substitution, crop-livestock specialization, agrarian class conflicts, gender inequality, democratic processes (Isgren and Ness, 2017; Misra, 2018).

In turn, an agroecological transition is being proposed to restructure socioeconomic and political aspects in food systems

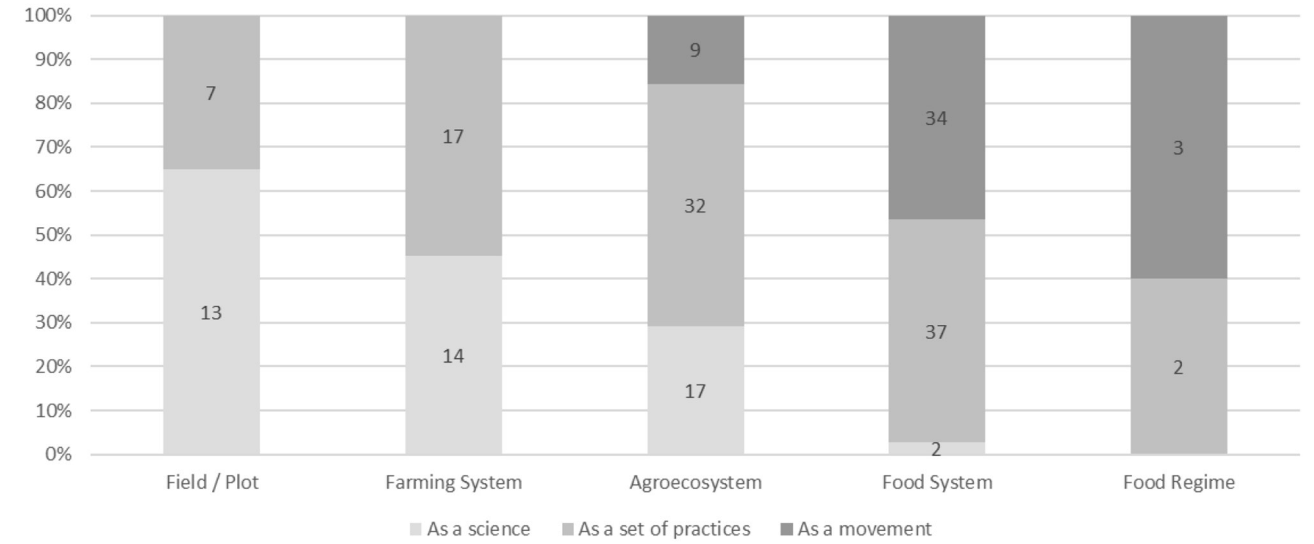

FIGURE 4 | Distribution of agroecological scale by the domain of agroecology considered in the articles.

to achieve a healthy, human-rights-based, and democratic decision-making process (Isgren and Ness, 2017; Misra, 2018). This relates closely to the food sovereignty movement that incorporates vital cultural significance into traditional knowledge and praxis (Wyckhuys and O'Neil, 2007; Acevedo-Osorio et al., 2017; Addinsall et al., 2017; Isgren and Ness, 2017; van Niekerk and Wynberg, 2017; Stein et al., 2018; Bezerra et al., 2019).

Use and Position of Participatory Methods

A balance of social science and life/natural science methods is applied among the case studies in our corpus. When comparing the agroecological types and methods (see **Figure 5** and **Supplementary Figure S3**), we observed that case studies conceptualize agroecology as a set of practices or as a movement when the research focus was within the social sciences. In comparison, life/natural science methods were used in case studies conceiving agroecology as a science or as a set of practices.

Ethnographic methods such as interviews (semi-structured and in-depth) and observations represent the majority ($n = 84/145$). Moreover, socio-econometric methods based on household surveys/questionnaires were well-represented, focusing mainly on the analysis of quantitative social phenomena.

One-sixth of the case studies ($n = 23/145$) employ participatory methods, including participatory rural appraisal (PRA), rapid rural appraisal (RRA), participatory learning, and PAR. As shown in **Figure 5**, participatory methods mainly focus on agroecology either as a set of practices or as a movement. All those case studies employ ethnographic methods (interviews and observation) and many use focus groups ($n = 12/23$), workshops ($n = 6/23$), and sociograms ($n = 7/23$). The scale of the studies focuses mainly on smallholder farming systems (Holt-Giménez, 2002; Guzmán et al., 2012; Hellin et al., 2013; Apgar et al., 2017), and in some cases specifically on autochthonous communities (Apgar et al., 2017; Lanka et al., 2017; Stein et al., 2018) or with a gendered focus (van Niekerk and Wynberg, 2017; Stein et al., 2018).

Farming communities are often engaged in research through cooperatives and formal associations (Holt-Giménez, 2002; Guzmán et al., 2012; Rogé et al., 2014; Acevedo-Osorio et al., 2017; Apgar et al., 2017; Isgren and Ness, 2017; Lanka et al., 2017) with a purposive selection of the population targeted by researchers (Holt-Giménez, 2002; Rogé et al., 2014; Ryschawy et al., 2017). In addition, some authors are looking to "confront" the knowledge between internal informants (mainly farmers) and external informants (mainly academics and experts) as a crucial part of the participatory approach (Cools et al., 2003; Hellin et al., 2013; Rogé et al., 2014; Addinsall et al., 2017; Ryschawy et al., 2017). Such studies aim to shed light on various perspectives on the agroecological transition, often pushed further *via* multi-stakeholder view analysis (Ryschawy et al., 2017; Simon et al., 2017, as in Borremans et al., 2018).

Above all, applications of participatory methods are diverse, reflecting various methodological approaches and agroecological positions. For example, several case studies applied focus groups with an extractive position, that is, as passive participation in which participants are consulted on a particular topic without opening space for co-learning, interaction, and potential self-mobilization (Hellin et al., 2013; Tran, 2013; Rogé et al., 2014; Addinsall et al., 2017; Lanka et al., 2017; van Niekerk and Wynberg, 2017; Borremans et al., 2018; Misra, 2018; Bezerra et al., 2019). In addition, PRA techniques in some studies consider a more reflexive approach. A popular one is participatory mapping, creating a space of discourse and visual support for knowledge sharing (Imbruce, 2007; van Niekerk and Wynberg, 2017). Other PRA exercises frequently employed are scoring techniques (Johansson et al., 2013) and sociograms (Bergquist et al., 2012; Guzmán et al., 2012). In the case of Bergquist et al. (2012), sociograms of energy flow systems

	As a Science	As a set of practices	As a movement
Ethnographic Methods	8	61	38
Agronomic Methods	20	21	1
Socio-Econometrics Methods	5	20	7
Participatory Methods	3	19	8
Biological and Ecological Methods	17	16	1
Modelling	7	7	
Geographical Measurements	3	5	
Life Cycle Analysis	2	3	
Historical Analysis	1	3	1
Water Sampling & Measurements	2	4	
EROI	2	1	
Policy Analysis Methods			3

FIGURE 5 | Distribution of case studies according to the type of methods applied and the field of agroecology conceptualized. The gray bar in column and row labels represents the frequency.

were designed to co-construct knowledge and compared expert knowledge with academic knowledge.

Some research underlines the importance of participatory methods as a set of tools to (co)-design a more sustainable agroecosystem and food system (Halbe et al., 2014; Ryschawy et al., 2017; Prost et al., 2018). The extensionist approach, whereby technicians and academics provide a step-by-step implementation of the new portfolio of practices, is substituted by an approach that allows farmers to design their action plan and strategies (Ryschawy et al., 2017; Prost et al., 2018). Thus, farmers become participants in the research for agroecosystem design, providing their knowledge and expertise throughout the process (Ryschawy et al., 2017; Simon et al., 2017). Participatory methods then become tools to merge autochthonous/local/traditional and academic knowledge for the co-construction of alternative land uses and shared governability of resources (Bergquist et al., 2012; Apgar et al., 2017; Stein et al., 2018), thus embedding the agroecological transition within the participatory methods (Bezerra et al., 2019). Furthermore, as Hellin et al. (2013) stated, participatory action research offers more tools to elaborate concrete *praxis* of the agroecological transition adapted to the communities' livelihood and priorities.

Only six articles reported the application of participatory action research. For example, Holt-Giménez (2002) demonstrated the link between PAR and the agroecological movement based on the farmer-to-farmer methodology (campesino-a-campesino) that has surged in Nicaragua. Here, participatory methods co-construct an assessment of impact of natural hazards on conventional agricultural plots and agroecological plots. Farmers' associations and research teams collaborate to create such assessments and the study renders well the habit (the praxis) of researching by the campesino-a-campesino movement.

As Apgar et al. (2017) mention, the framework of PAR aims to empower the communities (as an internal informant) for the research object/subject to say: "… the community in question decides, steers, and guides the research…" (p. 60). As such, the research team (as an external actor) is not the leading designer of the research but provides only guidelines and facilitates the research process. Isgren and Ness (2017) demonstrated that PAR could trigger this institutionalization (or associativity) and provide more farmer-to-farmer strategic planning and autonomy. As Bezerra et al. (2019) emphasized, agroforestry, and agroecological transition depend on applying those methods to encourage participatory learning, collective action, empowerment, and autonomy.

Guzmán et al. (2012) stated that the agroecological transition moves forward by applying PAR techniques to induce direct implementation. The study provides a straightforward methodology and techniques of PAR for designing and implementing agroecological practices, and, in parallel, encourages an agroecological movement in the study areas. The assessment of agroecological practices led to the development of local sustainable food networks with the communities' active participation.

Agroecology, Participatory Methods, and Epistemic Perspective

As shown previously, agroecological positioning intertwines with the methodological objective: how the researcher's position on agroecology connects with the methodological position, and subsequent participatory methods employed. We call this the epistemic perspective.

Most of the articles have a perspective on knowledge production as an in-depth analysis of a specific context, such as exploring the impacts of agroecological practices on smallholder livelihoods (Cools et al., 2003; Imbruce, 2007; Addinsall et al., 2017). These articles explore the synergies between the design of agroecological agroecosystems and livelihoods, conservation, ecosystem services, home gardening, food security, and sovereignty (Cools et al., 2003; Imbruce, 2007; Tran, 2013; Halbe et al., 2014; Addinsall et al., 2017; Lanka et al., 2017; van Niekerk and Wynberg, 2017; Stein et al., 2018). This analytical position often calls for repeating the study in another context to provide more evidence of the potential of agroecology (principle of replicability) and deepening research questions (Hellin et al., 2013). Furthermore, various case studies call for deepening their studies on the grounds of a new conceptual framework applied to agroecological studies filling (new) research gaps (Imbruce, 2007; Wyckhuys and O'Neil, 2007; Bergquist et al., 2012; Halbe et al., 2014; Rogé et al., 2014; Addinsall et al., 2017; Lanka et al., 2017; van Niekerk and Wynberg, 2017; Prost et al., 2018).

Even when staying with the analytical process, this epistemic position is not purely monolithic: the researcher as an observer of reality and the "researched" as observation subjects. As we saw in the previous section, participatory methods extend the interaction with farmers and communities. An analytical position can be enriched by the participation of the research communities, even in a consultative position, to better understand their perceptions, priorities, and knowledge (Wyckhuys and O'Neil, 2007; Bergquist et al., 2012; Rogé et al., 2014; Stein et al., 2018).

Developing knowledge for formulating recommendations is a step further than keeping to a strict analytical position. Some authors mentioned a lack of employing autochthonous knowledge and local indicators to adjust recommendations to the context of the study area (Cools et al., 2003; Acevedo-Osorio et al., 2017). This allows constructing and co-designing better agroecosystem alternatives based on agroecological principles (Acevedo-Osorio et al., 2017; Isgren and Ness, 2017; Simon et al., 2017; Prost et al., 2018; Stein et al., 2018). Some authors emphasize the imperative for further research to highlight the perspectives of multi-actors in developing research incentives and development programs (Hellin et al., 2013; Borremans et al., 2018). As such, other authors recommend including smallholders and autochthonous viewpoints on the design of sustainable agroecosystems in public policies (Rogé et al., 2014; Ryschawy et al., 2017; Simon et al., 2017). Going further, Misra (2018, 485) suggests the necessity to democratize and reform the agricultural sector by empowering smallholders in decision-making over the food system that include agroecological and food sovereignty principles and subsequently improve their livelihoods. Isgren and Ness (2017) analyze agroecological transition potential and recommend in addition better transformative frameworks to foster agroecological implementation and movements.

The rationale of transformative knowledge production (a transformative epistemic perspective) occurred in our corpus. Thus, some case studies use research capacities to foster agroecological transition, notably *via* participatory (action) research methods. A transformative epistemic perspective employs participatory methods to identify local indicators and implement alternative practices, leading to farmers' design and direct application of sustainable agriculture (Holt-Giménez, 2002; Acevedo-Osorio et al., 2017; Bezerra et al., 2019). For example, in Holt-Giménez (2002), knowledge production is generated in collaboration with researchers and farmers, resulting from a long history of peasant-to-peasant movements aiming to emancipate rural communities.

The co-construction of knowledge with farmers is critical for agroecological transition as it explores communities' self-determination in the design of their sustainability (Apgar et al., 2017; Stein et al., 2018; Bezerra et al., 2019). It thus engages the researcher to work with established farming communities such as cooperatives and farmer associations (Holt-Giménez, 2002; Guzmán et al., 2012; Acevedo-Osorio et al., 2017; Apgar et al., 2017; Bezerra et al., 2019). Furthermore, as shown in Rogé et al. (2014, 807), participatory methods stimulate the communities to undertake self-determination by thinking about community-driven education and organizing collective action.

Finally, knowledge production with a transformative objective is a continuous process linked to collective action and decision-making in ecosystem management by and for the communities (Holt-Giménez, 2002; Rogé et al., 2014; Apgar et al., 2017). For example, the case of Guzmán et al. (2012) shows an iterative process based on a long-term vision to build and expand an agroecological food system. Furthermore, transformative science means that researchers are no longer external academic observers but part of a specific socio-historical context; consequently, the research design must include non-academics (Guzmán et al., 2012; Apgar et al., 2017).

DISCUSSION

Our systematic review shows that the broad agroecological research scope encompasses the three types of agroecology indicated by Wezel et al. (2009)—as science, as a set of practices, and social movement. We can see a majority of publications focusing on agroecology as a set of practices. This is not surprising, as most case studies focus on agronomic research, comparing practices and their effects on agroecosystems. However, our study shows that an in-depth analysis blurs the frontier between agroecology as science, a set of practices, and a movement. It supports the point made by Wezel et al. (2009) that the categorizing of agroecology could be fuzzy as its meanings are linked to cultural and socio-historical aspects. Therefore, the categorization is functional but always should be managed with care and not hinder the richness of agroecological positions taken by various studies.

Most case studies examining agroecology as a movement were located in the Americas, particularly in South America, whereas agroecology as a set of practices mostly occurs in North America, Central America, and Europe. It shows that the trends observed by Wezel et al. (2009) continued after more than a decade of their study. However, very few studies in Africa and Asia were found to use the agroecological typology of Wezel et al. (2009), despite calls for a global agroecological transition (De Schutter, 2010; Duru et al., 2015; Wezel et al., 2020). This does not necessarily preclude an agroecological transition taking place in Africa and Asia, but if that is the case, the science about it uses different terminology. Besides, our corpus shows a preponderant use of the AEZ type of agroecology in these regions. The meaning and application of AEZ might be out of the scope of agroecology as science, practices, and movement as it describes land use planning of a specific area for agriculture according to ecological and environmental conditions. Such polysemy of agroecology might lead to confusion of agroecology but reflect the "dispute" existing in the use of the concept: agroecology that connects science, *praxis*, and social movement against agroecology as a technical option for agricultural commodification (Giraldo and Rosset, 2018).

Our results align with Wezel et al. (2009), indicating that the broader the research scope (from agroecosystem to food system to food regime), the more likely the agroecology studied relates to practices and/or a movement. Such studies included interdisciplinary research using social and anthropological methods encouraging a more complex view of agroecology, notably by opening farmers' perspectives instead of solely focusing on a conformist view of agroecology. However, most authors in our corpus conceive agroecology as a path to sustainable practices and do not explicitly position their discourse through the lens of transformative or conformist agroecology (Levidow et al., 2014; Giraldo and Rosset, 2018).

Few studies in the literature reflected the use of participatory methods in the agroecological field ($n = 23/145$, 16%). The in-depth analysis of these articles highlights that agroecology is not solely a portfolio of practices but a necessary adaptation that farmers employ to secure their food system while preserving the environment (Acevedo-Osorio et al., 2017; Lanka et al., 2017; Ryschawy et al., 2017). This confirms the vital link between agroecology and food sovereignty as suggested in the literature (McMichael, 2014; La Vía Campesina., 2018). Above all, our corpus shows that the agroecological transition requires farmers to have an active role in research. Consequently, a shift of the researcher's positionality must occur in terms of understanding the *praxis* of agroecology and the *praxis* of conducting research.

Most case studies did not include communities in the research design process. While community participation in research is an attempt to shift the scientific role and position, there are different levels of participation. For example, several case studies employed focus groups as a participatory method, with which researchers can consult the participants' perceptions of the study subject instead of looking for active participation over the study object/subject. In other words, a focus group can be employed as an extractive method, in which farmers and communities are external informants and nothing else. This is very different from research where the communities appropriate the research object, including reflecting on objectives and expected outcomes, and farmers become researchers themselves. However, if such techniques support the exchange of knowledge and blur the barrier of the unilateral relation between researcher and "researched," the use of these participatory methods shows different epistemic objectives. Accordingly, conducting PRAs can trigger a sense of mobilization. For instance, Rogé et al. (2014) showed that farmers, thanks to workshops and participatory assessments, called for deepening these participatory assessments by organizing themselves to engage in better agroecosystem management together, that is, by organizing collective action. Nevertheless, the full scope of what such participatory methodology offers is often not undertaken. It is barely a tool for co-constructing analysis on a specific topic, and not to open space for planning actions consequent to the knowledge construction (as in Bergquist et al., 2012).

Participatory methods can explore other directions, notably more emancipatory ones (Holt-Giménez, 2002; Bergquist et al., 2012; Guzmán et al., 2012; Apgar et al., 2017; Stein et al., 2018). Agroecological implementation must be preceded by the inclusion of smallholders in action research design and thus be steered by them (Méndez et al., 2017; Pimbert, 2017). Co-constructing knowledge then becomes evidence for fostering the transition when end-users of this knowledge are communities and academics, testifying to the place of PAR between empowerment and emancipatory epistemologies. Empowering communities in the research process is strongly intertwined with those communities' institutionalization as producer cooperatives or community associations (as in Apgar et al., 2017; Isgren and Ness, 2017). Many authors of our corpus mentioned and demonstrated that such a research process needs to be iterative and inherently based on various long-term research cycles (Holt-Giménez, 2002; Guzmán et al., 2012; Apgar et al., 2017).

As mentioned in the Methods section, we based our systematic review on case studies reported in scientific articles, thus limiting our scope to peer-reviewed research with scientific standards that may not fully represent the breadth of PAR in agroecology. For instance, extensive experience in transforming the food system in various countries has been published in book sections not indexed in scientific databases (Pimbert et al., 2017). In addition, experiences of civil society organizations with transformative agroecology illustrating the importance of empowerment and PAR have often been published in the gray literature. Likewise, other emancipatory and participatory approaches contributing to the agroecological transition that have been hardly documented in the scientific literature may also be found in the gray literature. For instance, the Farmer Field School (FFS) approach—in which farmers identify their problems, set their research objectives, and conduct research themselves—has been documented to be both empowering and helping farmers to build human, social, and natural capital (van den Berg et al., 2020). FFS borrowed methodological aspects from the experiential learning cycle, the learner-centered approach in adult education, and the framework for the technical, practical, and emancipatory learning, which are common methodological approaches in PAR. FFSs have been implemented within the field of agroecology, for instance, within integrated pest management in Africa (FAO., 2018b), on participatory plant breeding or on local food plants for nutrition (Visser et al., 2018; Cruz-Garcia et al., 2020). In these examples, farmers integrate local and scientific/technical knowledge while exploring their own solutions.

Additionally, we are conscious that the use of Scopus and Web of Science does not represent the full scope of scientific literature in this field and adding more contextualized abstract citation databases could potentially have enriched our study (such as Latindex, Scielo, Redalyc, Dialnet, DOAJ, HAL, and CAIRN). We chose Scopus and Web of Science to ensure that we only included papers that are in peer-reviewed journals that undergo scrutiny before being indexed as is the case in many similar synthesis studies (Magliocca et al., 2015), but we acknowledge that it renders a somewhat narrower scope. Future studies on the importance of participatory and empowerment approaches for agroecological transformation focused on reviewing gray literature and other abstract and citation databases are recommended. It has significant implications for the inclusion of agroecological transition in policies on integrating such transition to empower smallholders in the choice of their food system.

CONCLUSIONS

Our study shows that, despite a need for transformative methods, such as participatory action research, to support the scale-up to an agroecological transition, these methods are not often used in case studies published in peer-reviewed articles. To further scale up the agroecological transition and achieve a global transition, one option can be broadening the scope of agroecological research in Africa and Asia, that is, focusing not solely on agroecology as science but addressing processes of the agroecological transition in these regions, using PAR and other participatory and empowering approaches. Additionally, understanding specific contexts and perspectives that bring agroecology to *praxis* in these regions should fill research gaps just as much for agroecological research as for PAR. Furthermore, with an environment that foster more democratic decision-making (*à la* Pimbert, 2017), PAR can offer farmers a space to trigger agroecological research, which is an essential component for a long-term vision and collective action.

However, this shift in epistemic perspective is a difficult task. Most of the experiences reflect a long-term relationship between farmers and researcher-activists (Holt-Giménez, 2002; Castellanet and Jordan, 2014; Méndez et al., 2017). Short-term project-based science, which is typically the way science is organized and conducted, hampers generating the long-term relationships necessary for successful PAR and the agroecological transition. To respond to such hindrance, Méndez et al. (2017) mentioned some experiences where projects are written within active consultation with smallholders, notably by sharing grant proposal documents and moving forward only when feedback is received. Therefore, changing the way science on agroecology is organized is necessary to provide researchers engaged in PAR with the time and resources needed to conduct studies that will advance more transformative agendas and achieve an agroecological transition (see for instance Pimbert, 2017; Pimbert et al., 2017). This opens the door to new questions on designing long-term PAR in agroecology when confronted with short-term project-based society.

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

ES, OM, J-FL, GC-G, and MB contributed to conception and design of the study. ES organized the database and performed the statistical analysis and in-depth analysis of articles. ES and OM wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, 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.2021.709401/full#supplementary-material

REFERENCES

Acevedo-Osorio, Á., Angarita Leiton, A., León Durán, M. V., and Franco Quiroga, K. L. (2017). Sustentabilidad y variabilidad climática: acciones agroecológicas participativas de adaptación y resiliencia socioecológica en la región alto-andina colombiana. *Luna Azul.* 44, 06–26. doi: 10.17151/luaz.2017.44.2

Addinsall, C., Weiler, B., Scherrer, P., and Glencross, K. (2017). Agroecological tourism: bridging conservation, food security and tourism goals to enhance smallholders' livelihoods on South Pentecost, Vanuatu. *J. Sustain. Tourism* 25, 1100–1116. doi: 10.1080/09669582.2016.1254221

Altieri, M. A. (1989). Agroecology: a new research and development paradigm for world agriculture. *Agric. Ecosyst. Environ.* 27, 37–46. doi: 10.1016/B978-0-444-88610-1.50006-1

Altieri, M. A., and Nicholls, C. I. (2005). *Agroecology and the Search for a Truly Sustainable Agriculture*. Mexico: PNUMA; UNEP.

Altieri, M. A., and Toledo, V. M. (2011). The agroecological revolution in Latin America: rescuing nature, ensuring food sovereignty and empowering peasants. *J. Peasant Stud.* 38, 587–612. doi: 10.1080/03066150.2011.582947

Andreotti, F., Speelman, E. N., Van den Meersche, K., and Allinne, C. (2020). Combining participatory games and backcasting to support collective scenario evaluation: an action research approach for sustainable agroforestry landscape management. *Sustain. Sci.* 15. 1383–1399. doi: 10.1007/s11625-020-00829-3

Apgar, J. M., Mustonen, T., Lovera, S., and Lovera, M. (2017). Moving beyond co-construction of knowledge to enable self-determination. *IDS Bull.* 47(6):55–72. doi: 10.19088/1968-2016.199

Armitage, D. R., Plummer, R., Berkes, F., Arthur, R. I., Charles, A. T., Davidson-Hunt, I. J., et al. (2009). Adaptive co-management for social-ecological complexity. *Front. Ecol. Environ.* 7, 95–102. doi: 10.1890/070089

Barling, L., Crossley, D., Cura, A., and Mulvany, J. (2018). *For Whom? Qestioning the Food and Farming Research Agenda*. London: Food Ethics Council.

Bergquist, D. A., Cavalett, O., and Rydberg, T. (2012). Participatory emergy synthesis of integrated food and biofuel production: a case study from Brazil. *Environ. Dev. Sustain.* 14, 167–182. doi: 10.1007/s10668-011-9314-8

Bezerra, L. P., Franco, F. S., Souza-Esquerdo, V. F., and Borsatto, R. (2019). Participatory construction in agroforestry systems in family farming: ways for the agroecological transition in Brazil. *Agroecol. Sustain. Food Syst.* 43, 180–200. doi: 10.1080/21683565.2018.1509167

Bohensky, E. L., and Maru, Y. (2011). Indigenous knowledge, science, and resilience: what have we learned from a decade of international literature on 'integration'? *Ecol. Soc.* 16:art6. doi: 10.5751/ES-04342-160406

Borremans, L., Marchand, F., Visser, M., and Wauters, E. (2018). Nurturing agroforestry systems in Flanders: analysis from an agricultural innovation systems perspective. *Agric. Syst.* 162, 205–219. doi: 10.1016/j.agsy.2018.01.004

Castellanet, C., and Jordan, C. F. (2014). *Participatory Action Research in Natural Resource Management A Critque of the Method Based on Five Years' Experience in the Transamozonica Region of Brazil*. New York, NY: Taylor and Francis.

Chambers, R. (2015). Inclusive rigour for complexity. *J. Dev. Effect.* 7, 327–335. doi: 10.1080/19439342.2015.1068356

Chaparro-Africano, A.-M., and Naranjo, S. E. (2020). Participatory system of guarantees - PSG of the Red de Mercados Agroecológicos de Bogotá Región RMABR. A contribution to the sustainability of agroecological producers and markets. *Int. J. Agric. Sustain.* 18, 456–472. doi: 10.1080/14735903.2020.1793614

Cools, N., De Pauw, E., and Deckers, J. (2003). Towards an integration of conventional land evaluation methods and farmers' soil suitability assessment: a case study in northwestern Syria. *Agric. Ecosyst. Environ.* 95, 327–342. doi: 10.1016/S0167-8809(02)00045-2

Cruz-Garcia, G., Visser, B., Nera, E., and Salazar, R. (2020). *Field Guide for Farmer Field Schools on Nutrition and Local Food Plants*. Oxfam Novib, Field Guide.

De Schutter, O. (2010). *Report Submitted by the Special Rapporteur on the Right to Food, Olivier De Schutter*. New York, NY: United Nation General Assembly, No. A/HRC/16/49.

De Schutter, O., and Vanloqueren, G. (2011). The new green revolution: how twenty-first-century science can feed the world. *Solutions* 2, 33–44.

Duru, M., Therond, O., and Fares, M. (2015). Designing agroecological transitions; A review. *Agron. Sustain. Dev.* 35, 1237–1257. doi: 10.1007/s13593-015-0318-x

European Union. (2017). *Joint Statement by the Council and the Representatives of Governments of the Member States Meeting Within the Council, the European Parliament and the Commission. The New Eiropean Consensus on Development 'Our World, Our Dignity, Our Future'.*

Fals Borda, O. (2013). Action research in the convergence of disciplines. *Int. J. Action Res.* 9, 155–167. doi: 10.1688/1861-9916_IJAR_2013_02_Fals-Borda

FAO. (1996). *Agro-Ecological Zoning. Guidelines*. Soil Resources, Management and Conservation Service FAO Land and Water Development Division, Bulletin No. *73*.

FAO. (2018a). *Agroecology | Family Farming Knowledge Platform | Food and Agriculture Organization of the United Nations*. Food and Agriculture Organization of the United Nations. Available online at: http://www.fao.org/family-farming/themes/agroecology/en/ (accessed April 04, 2018).

FAO. (2018b). Integrated Management of the Fall Armyworm On Maize: A Guide for Farmer Field Schools in Africa. Food and Agriculture Organization of the United Nations. Rome: FAO.

Fernández, M. (2006). "Practicing agroecology, using local knowledge," in *Agroecology and the Struggle for Food Sovereignty in the Americas*, eds. A. Cohn, J. Cook, M. Fernández, R. Reider,and C. Steward (Nottingham, UK: IIED, CEESP and Yale F&ES), 138–41.

Fischer, G., Prieler, S., and van Velthuizen, H. (2005). Biomass potentials of miscanthus, willow and poplar: results and policy implications for Eastern Europe, Northern and Central Asia. *Biomass Bioenergy* 28, 119–132. doi: 10.1016/j.biombioe.2004.08.013

Francis, C., Lieblein, G., Gliessman, S., Breland, T. A., Creamer, N., Harwood, R., et al. (2003). Agroecology: the ecology of food systems. *J. Sustain. Agric.* 22, 99–118. doi: 10.1300/J064v22n03_10

Giraldo, O. F., and Rosset, P. M. (2018). Agroecology as a territory in dispute: between institutionality and social movements. *J. Peasant Stud.* 45, 545–564. doi: 10.1080/03066150.2017.1353496

Gliessman, S. R. (2015). Agroecology: the Ecology of Sustainable Food System, 3rd Edn. Boca Raton, FL: CRC Press.

Guzmán, G. I., López, D., Román, L., and Alonso, A. M. (2012). Participatory action research in agroecology: building local organic food networks in Spain. *J. Sustain. Agric.* 37, 126–146. doi: 10.1080/10440046.2012.718997

Halbe, J., Adamowski, J., Bennett, E. M., Pahl-Wostl, C., and Farahbakhsh, K. (2014). Functional organization analysis for the design of sustainable engineering systems. *Ecol. Eng.* 73, 80–91. doi: 10.1016/j.ecoleng.2014.08.011

Hellin, J., Erenstein, O., Beuchelt, T., Camacho, C., and Flores, D. (2013). Maize stover use and sustainable crop production in mixed crop-livestock systems in Mexico. *Field Crops Res.* 153, 12–21. doi: 10.1016/j.fcr.2013.05.014

HLPE. (2019). Agroecological and Other Innovative Approaches for Sustainable Agriculture and Food Systems That Enhance Food Security and Nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Rome: FAO, No. 14.

Holt-Giménez, E. (2002). Measuring farmers' agroecological resistance after Hurricane Mitch in Nicaragua: a case study in participatory, sustainable land management impact monitoring. *Agric. Ecosyst. Environ.* 93, 87–105. doi: 10.1016/S0167-8809(02)00006-3

Huntington, H. P. (2011). The local perspective. *Nature* 478, 182–183. doi: 10.1038/478182a

Imbruce, V. (2007). Bringing Southeast Asia to the Southeast United States: new forms of alternative agriculture in Homestead, Florida. *Agric. Hum. Values* 24, 41–59. doi: 10.1007/s10460-006-9034-0

Isgren, E., and Ness, B. (2017). Agroecology to promote just sustainability transitions: analysis of a civil society network in the Rwenzori Region, Western Uganda. *Sustainability* 9:1357. doi: 10.3390/su9081357

Johansson, K.-E., Axelsson, R., and Kimanzu, N. (2013). Mapping the relationship of inter-village variation in agroforestry tree survival with social and ecological characteristics: the case of the Vi Agroforestry Project, Mara Region, Tanzania. *Sustainability* 5, 5171–5194. doi: 10.3390/su5125171

Kesby, M., Kindon, S., and Pain, R. (2007). "Participation as a form of power. Retheorising empowerment and spatialising participatory action research, in *Participatory Action Research Approaches and Methods. Connecting People, Participation and Place*, ed. S. Kindon (London; New York, NY: Routledge Taylor and Francis Group), 19–25.

Kindon, S., Pain, R., and Kesby, M. (2007a). "Participatory action research: origins, approaches and methods," in *Participatory Action Research Approaches and Methods. Connecting People, Participation and Place*, eds S. Kindon, R. Pain, and M. Kesby (London; New York, NY: Routledge Taylor & Francis Group), p. 9–18.

Kindon, S., Pain, R., and Kesby, M. (eds.). (2007b). "Introduction: connecting people, participation and place," in *Participatory Action Research Approaches and Methods. Connecting People, Participation and Place* (London; New York, NY: Routledge Taylor and Francis Group). pp. 1–6.

La Vía Campesina. (2018). *The Time has Come to Scale Up Peasant Agroecology: La Via Campesina at the II International Agroecology Symposium of FAO*. Via Campesina English. Available online at: https://viacampesina.org/en/the-time-has-come-to-scale-up-peasant-agroecology-la-via-campesina-delegation-at-the-2nd-international-agroecology-symposium-of-fao/ [accessed April 16, 2018].

Lanka, S. V., Khadaroo, I., and Böhm, S. (2017). Agroecology accounting: biodiversity and sustainable livelihoods from the margins. *Account. Audit. Account. J.* 30, 1592–1613. doi: 10.1108/AAAJ-12-2015-2363

Levidow, L., Pimbert, M., and Vanloqueren, G. (2014). Agroecological research: conforming-or transforming the dominant agro-food regime? *Agroecol. Sustain. Food Syst.* 38, 1127–1155. doi: 10.1080/21683565.2014.951459

Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P. A., et al. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. *Ann. Intern. Med.* 151:W65. doi: 10.1371/journal.pmed.1000100

Magliocca, N. R., Rudel, T. K., Verburg, P. H., McConnell, W. J., Mertz, O., Gerstner, K., et al. (2015). Synthesis in land change science: methodological patterns, challenges, and guidelines. *Region. Environ. Change* 15, 211–226. doi: 10.1007/s10113-014-0626-8

Mauser, W., Klepper, G., Rice, M., Schmalzbauer, B. S., Hackmann, H., Leemans, R., et al. (2013). Transdisciplinary global change research: the co-creation of knowledge for sustainability. *Curr. Opin. Environ. Sustain.* 5, 420–431. doi: 10.1016/j.cosust.2013.07.001

McMichael, P. (2014). Historicizing food sovereignty. *J. Peasant Stud.* 41, 933–957. doi: 10.1080/03066150.2013.876999

Méndez, V., Caswell, M., Gliessman, S., and Cohen, R. (2017). Integrating agroecology and participatory action research (PAR): lessons from Central America. *Sustainability* 9:705. doi: 10.3390/su9050705

Migliorini, P., and Wezel, A. (2017). Converging and diverging principles and practices of organic agriculture regulations and agroecology. A review. *Agron. Sustain. Dev.* 37:63. doi: 10.1007/s13593-017-0472-4

Misra, M. (2018). Moving away from technocratic framing: agroecology and food sovereignty as possible alternatives to alleviate rural malnutrition in Bangladesh. *Agric. Hum. Values* 35, 473–487. doi: 10.1007/s10460-017-9843-3

Moher, D., Liberati, A., Tetzlaff, J., and Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Ann. Intern. Med.* 151, 264–269. doi: 10.7326/0003-4819-151-4-200908180-00135

Pimbert, M. (2017). Agroecology as an alternative vision to conventional development and climate-smart agriculture. *Development* 58, 286–298. doi: 10.1057/s41301-016-0013-5

Pimbert, M., Satheesh, P. V., Argumedo, A., and Farvar, T. M. (2017). "Participatory action research transforming local food systems in India, Iran and Peru," in *People's Knowledge Editorial Collective, Everyday Experts: How People's Knowledge Can Transform the Food System* (Conventry: Centre for Agroecology, Water and Resilience (CAWR)), 98–119.

Prost, L., Reau, R., Paravano, L., Cerf, M., and Jeuffroy, M.-H. (2018). Designing agricultural systems from invention to implementation: the contribution of agronomy. Lessons from a case study. *Agric. Syst.* 164, 122–132. doi: 10.1016/j.agsy.2018.04.009

Rogé, P., Friedman, A. R., Astier, M., and Altieri, M. A. (2014). Farmer strategies for dealing with climatic variability: a case study from the Mixteca Alta Region of Oaxaca, Mexico. *Agroecol. Sustain. Food Syst.* 38, 786–811. doi: 10.1080/21683565.2014.900842

Rosset, P. M., and Altieri, M. A. (2017). *Agroecology Science and Politics.* Rugby: Practical Action Publishing.

Ryschawy, J., Martin, G., Moraine, M., Duru, M., and Therond, O. (2017). Designing crop-livestock integration at different levels: Toward new agroecological models? *Nutr. Cycl. Agroecosyst.* 108, 5–20. doi: 10.1007/s10705-016-9815-9

Sabourin, E., Patrouilleau, M. M., Le Coq, J.-F., Vasquez, L., and Niederle, P. (2017). *Políticas Públicas a Favor de le Agroecología En América Latina y el Caribe*. Porto Alegre: Red PP-AL. FAO.

Simon, S., Lesueur-Jannoyer, M., Plénet, D., Lauri, P.-É., and Le Bellec, F. (2017). Methodology to design agroecological orchards: Learnings from on-station and on-farm experiences. *Eur. J. Agron.* 82, 320–330. doi: 10.1016/j.eja.2016.09.004

Stassart, P. M., Baret, P., Grégoire, J.-C., Hance, T., Mormont, M., Reheul, D., et al. (2012). "Chapitre 1. L'agroécologie: trajectoire et potential," in *Pour une transition vers des systémes alimentaires durables*, eds D. Van Dam, M. Streith, J. Nizet, and P. M. Stassart (Dijon cedex: Éducagri éditions), 25–51.

Stein, K., Mirosa, M., and Carter, L. (2018). Māori women leading local sustainable food systems. *Alternative* 14, 147–155. doi: 10.1177/1177180117753168

Tran, T. T. T. (2013). Food safety and the political economy of food governance: the case of shrimp farming in Nam Dinh Province, Vietnam. *J. Peasant Stud.* 40, 703–719. doi: 10.1080/03066150.2013.826653

van den Berg, H., Phillips, S., Dicke, M., and Fredrix, M. (2020). Impacts of farmer field schools in the human, social, natural and financial domain: a qualitative review. *Food Security* 12, 1443–1459. doi: 10.1007/s12571-020-01046-7

van Niekerk, J., and Wynberg, R. (2017). Traditional seed and exchange systems cement social relations and provide a safety net: a case study from KwaZulu-Natal, South Africa. *Agroecol. Sustain. Food Syst.* 41, 1099–1123. doi: 10.1080/21683565.2017.1359738

Visser, E. B., Salazar, R., van Oudenhoven, F., and Manicad, G. (2018). *Facilitators' Field Guide for Farmer Field Schools on Participatory Plant Breeding (Focused on Maize, Pearl Millet, Sorghum and Groundnut)*. Harare: Community Technology Development Trust (CTDT), Field Guide.

Wezel, A., Bellon, S., Doré, T., Francis, C., Vallod, D., and David, C. (2009). Agroecology as a science, a movement and a practice. A review. *Agron. Sustain. Dev.* 29, 503–515. doi: 10.1051/agro/2009004

Wezel, A., Herren, B. G., Kerr, R. B., Barrios, E., Gonçalves, A. L. R., and Sinclair, F. (2020). Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. *Agron. Sustain. Dev.* 40:40. doi: 10.1007/s13593-020-00646-z

Wezel, A., and Jauneau, J.-C. (2011). "Agroecology - interpretations, approaches and their links to nature conservation, rural development and ecotourism," in *Integrating Agriculture, Conservation and Ecotourism: Examples from the Field*, eds. W. B. Campbell, and S. Lopez Ortiz (Dordrecht: Springer Netherlands), 1–25.

Wyckhuys, K. A. G., and O'Neil, R. J. (2007). Local agro-ecological knowledge and its relationship to farmers' pest management decision making in rural Honduras. *Agric. Hum. Values* 24, 307–321. doi: 10.1007/s10460-007-9068-y

Yin, R. K. (2009). *Case Study Research, 4th Edn*. Thousand Oaks, CA: SAGE Publications.

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Future Policy Award 2018: The Good Food Purchasing Program, USA

Paula Daniels[1]* *and Alexa Delwiche*[2]*

[1] Center for Good Food Purchasing, Los Angeles, CA, United States, [2] Center for Good Food Purchasing, Berkeley, CA, United States

Adopted first by the City of Los Angeles in 2012, the Good Food Purchasing Program® creates a transparent supply chain and helps institutions to measure and then make shifts in their food purchases. It is the first procurement model to support five food system values—local economies, environmental sustainability, valued workforce, animal welfare and nutrition—in equal measure and thereby encourages myriad organizations to come together to engage for shared goals. Within just six years, the Good Food Purchasing Program has catalyzed a nationwide movement to establish similar policies in localities small and large across the United States, and inspired the creation of the Center for Good Food Purchasing. First adopted by the City of Los Angeles in 2012, it is a procurement standard that offers institutions a system in which current investments toward food are redirected toward more sustainable and fair suppliers. It uses a metric-based, flexible framework that produces a star rating. The Good Food Purchasing Program promotes the purchase of more sustainably produced food, from local economies, especially smaller and mid-sized farms and other food processing operations, which results in production returns at a more regional and local level, and ensures that suppliers' workers are offered safe and healthy working conditions and fair compensation, that livestock receives healthy and humane care, and that consumers—foremost school children, patients, the elderly—enjoy better health and well-being as a result of higher quality nutritious meals. This article will detail its implementation since 2012, provide current information on the impacts the Program has had on the agroecology of regions in the US food system, and recommendations for policy changes that could catalyze more accelerated impact.

Keywords: purchasing power, institutions, GFPP, Los Angeles, values, transparency equitable, sustainability, regional food system

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***Correspondence:**
Alexa Delwiche
adelwiche@goodfoodpurchasing.org
Paula Daniels
pdaniels@goodfoodpurchasing.org

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INTRODUCTION

Adopted first by the City of Los Angeles in 2012, the Good Food Purchasing Program (the Program or GFPP) is a procurement program[1] that fosters a transparent regional food supply chain and helps institutions to measure and then make shifts in their food purchases. It is the first procurement model designed to elevate government based food service as a transformative tool, using its significant purchasing power to support five food system values—local economies, environmental

[1] *GFFP Standards, September 2017*. Available online at: *https://gfpp.app.box.com/v/GFPPStandards2017* (accessed June 17, 2020).

sustainability, valued workforce, animal welfare, and nutrition—in equal measure. Its adoption model encourages organizations to collaborate toward shared goals. The Program offers institutions a feedback tool which helps them to redirect food budgets toward more sustainable and high road suppliers.

Using a metric-based, flexible framework that produces a star rating, the Program promotes the purchase of more sustainably produced food from local economies, especially small- and mid-sized farms and other food processing operations, which results in production returns at a more regional and local level, ensures that suppliers' workers are offered safe and healthy working conditions and fair compensation, that livestock receives healthy and humane care, and that consumers—foremost school children, patients, the elderly—enjoy better health and well-being thanks to higher quality nutritious meals. Within just 6 years, the Program achieved impressive impact, and has now expanded to 20 cities and enrolled over 45 municipal institutions across the country. The systemically holistic Good Food Purchasing Program was given favorable mention in 2018[2] by the World Future Council, the Food and Agriculture Organization of the United Nations (FAO), and IFOAM Organics International.

THE GOOD FOOD PURCHASING PROGRAM

Program Development, Expansion, and Impact

California is the world's fifth largest supplier of food, cotton fiber, and other agricultural commodities, the largest producer of food in the U.S.[3], and in 2018 was the world's fifth largest economy surpassing that of the United Kingdom[4]. The Greater Los Angeles Area is the nation's second-most populous urban region in the United States, with 18.7 million residents as of 2015[5]. The City of Los Angeles is the most populous of the many cities in the region (it is the second largest city in the country) and in 2018 the Greater Los Angeles metropolitan area had the third largest gross metropolitan product in the world at nearly $1trillion, behind New York and Tokyo[6]. It is the de facto leader of the Southern California region in terms of economic and other influence.

In September 2009, Los Angeles Mayor Antonio Villaraigosa announced the creation of the Los Angeles Food Policy Task Force. The announcement came as a key inflection point in the development of a regional food policy initiative, which was the conception and project of the author of this article, Paula Daniels, who was then a senior member in the administration of Mayor Villaraigosa, serving at the time as Commissioner with the Board of Public Works. Commissioner Daniels undertook to research and advocate for the City of Los Angeles to develop and advance a regional food policy framework to which the Mayor agreed. Along with the announcement of the creation of the Los Angeles Food Policy Task Force, was the Mayor's directive to prepare a report with recommendations to address certain key food system issues, including whether or not there should be a food policy council. The Mayor designated Commissioner Daniels to lead the task force; she then recruited the membership of the task force, with input from staff members of the Urban and Environmental Policy Institute of Occidental College.

The membership of the Task Force was a careful process of curation, with criteria for inclusion based on: (1) food system sector representation; (2) well-recognized leadership in their respective field; (3) gender and ethnic diversity; (4) ability to function well-enough in a team context to be able to synthesize ideas for a report (see **Figure 1** for a list of the Task Force members).

Concurrently, Commissioner Daniels secured funding for a staff position to assist in coordinating the work of the Task Force. Alexa Delwiche (co-author of this report) was hired as Task Force Coordinator and played a role in stakeholder engagement and program development.

The Task Force convened in November 2009 and was charged with developing a food policy framework for Los Angeles as the head of the Southern California region. The task force adopted a goal of becoming a "Good Food" region, with "Good Food" defined as food that is healthy, affordable, fair and sustainable. Over the course of 10 months, Task Force members conducted strategy sessions and developed a policy platform, incorporating input from over 200 cross sector individuals and organizations in extensively curated roundtable discussions and listening sessions. In July 2010, the Task Force released a report called the Good Food for All Agenda, which described the then existing food system challenges of Los Angeles, as follows:

> Our current sources of food largely consist of cheap, high calorie, low nutrient and highly processed food, often shipped from far away and grown by unsustainable practices. Industrial farms and the extensive transportation of their output debilitate the natural environment through water use, chemical impacts, and air quality. At the same time, the health and well-being of farm and food workers are often sacrificed to meet demands for cheaper food…
> Because of persistent poverty and growing unemployment in Los Angeles, hunger has remained a chronic problem in the region. For many families, the consumption of too many cheap calories and too little exercise has caused a diabetes and obesity epidemic. Good Food is not available in many low-income areas and neighborhoods of color…In these neighborhoods,

[2] *Good Food Purchasing Program*. FuturePolicy.org. Available online at: *https://www.futurepolicy.org/healthy-ecosystems/los-angeles-good-food-purchasing-program/* (accessed June 17, 2020).

[3] AG Hires. Available online at: *https://aghires.com/california-largest-food-producer-u-s/* (accessed June 17, 2020).

[4] "California is now the world's fifth-largest economy, surpassing United Kingdom" (Associated Press, May 4, 2018). Available online at: https://www.latimes.com/business/la-fi-california-economy-gdp-20180504-story.html (accessed June 25, 2020).

[5] US Census, Annual Estimates of the Resident Population: April 1, 2010 to July 1, 2015 - United States – Combined Statistical Area; and for Puerto Rico *https://archive.vn/20200213005001/http://factfinder.census.gov/bkmk/table/1.0/en/PEP/2015/GCTPEPANNR.US41PR*; 2019 updates available to download here: *https://www.census.gov/data/tables/time-series/demo/popest/2010s-total-metro-and-micro-statistical-areas.html*.

[6] US Bureau of Economic Analysis, CAGDP1 Gross Domestic Product (GDP) summary by county and metropolitan area. https://apps.bea.gov/itable/iTable.cfm?ReqID=70&step=1 Accessed June 25, 2020.

THE LOS ANGELES FOOD POLICY TASK FORCE

Martin Anenberg	Locally Grown Produce Specialist, FreshPoint of Southern California
Andrea Azuma	Project Manager, Community Benefit, Kaiser Permanente
Glen Dake	Landscape Architect, LA Community Garden Council
Paula Daniels	Commissioner, City of Los Angeles Board of Public Works
Gwendolyn Flynn	Project Director, Community Health Councils
Jonathan Gold	Food Critic, LA Weekly
Robert Gottlieb	Executive Director, Urban & Environmental Policy Institute, Occidental College
Renee Guilbault	Director of Food and Beverage, Le Pain Quotidien and West Central Produce
Karly Katona	Deputy, Office of Supervisor Mark Ridley-Thomas
Gregg Kettles	Deputy Counsel, Office of Mayor Antonio Villaraigosa
Mary Lee	Associate Director, PolicyLink
Miguel Luna	Executive Director, Urban Semillas
Elliott Petty	Director, Healthy Grocery Stores Project, Los Angeles Alliance for a New Economy
Bruce Saito	Executive Director, Los Angeles Conservation Corps
Matthew Sharp	Senior Advocate, California Food Policy Advocates
Jean Tremaine	Director, Nutrition Program, Los Angeles County Department of Public Health
Michael Woo	Dean, College of Environmental Design, California State Polytechnic University, Pomona
Alex Weiser	Farmer, Weiser Family Farms
Larry Yee	Advisor Emeritus, University of California Cooperative Extension, Ventura County and Roots of Change Stewardship Council

FIGURE 1 | Image from page ii of the report of the Los Angeles Food Policy Task Force, called Good Food for All Agenda (2010), available at https://static1.squarespace.com/static/5bc50618ab1a624d324ecd81/t/5be5da9bc2241b38ebd245a7/15.

convenience stores selling cheap, unhealthy foods overwhelm the neighborhood food environment.

The report recommended 55 action steps in six priority areas, directed toward the goal of building a more sustainable and equitable regional food system in the LA region of southern California[7]. Mayor Villaraigosa approved the report recommendations, and the Los Angeles Food Policy Council (LAFPC) was created as a result of one of the report recommendations.

Commissioner Daniels was named Chair of the LAFPC and along with the staff support of Alexa Delwiche, continued to develop the organizational infrastructure for it, including fundraising, staffing, staff development and mentorship, development of the organizational charter and mission, establishment of its non-profit status and fiscal sponsorship, and creation of the unique organizational structure of the LAFPC, as well as the creation of working groups to allow for unlimited stakeholder participation. As a senior city official, she secured meeting space for the council and the working groups at city facilities, and housed the growing staff of the LAFPC (for which she had raised funds) in her suite offices at City Hall (where the non-profit LAFPC continues to be housed as of this article).

The first meeting of the LAFPC was in January of 2011. Its membership was envisioned by the Task Force as a larger body than the Task Force itself, limited (in order to have balance of perspective) to two from each identified sector area. Most Task Force members also became LAFPC council members. (The vision for the LAFPC and its representation is found at pages 84–86 of the Good Food for All Agenda, fn 7). The initiative proved to be of great interest to the community at large, and participation in the working group meetings averaged well over 120 individuals representing various organizations. As a result of the increasing interest in and complexity of the LAFPC work, Mayor Villaraigosa named Paula Daniels as his Senior Advisor on Food Policy—the first such position at the senior staff level (equivalent to Deputy Mayor) in the country. By June of 2013, the end of Mayor Villaraigosa's second and final term in office, the LAFPC had grown to eight full time staff members operating as backbone, or secretariat, to the 40 member LAFPC council, and the hundreds of working group members (see **Figure 2** for a depiction of the working group membership).

[7]Good Food for All Agenda. *Los Angeles Food Policy Task Force* (2010) Available online at: https://goodfoodlosangeles.files.wordpress.com/2010/07/good-food-full_report_single_072010.pdf (accessed June 17, 2020).

FIGURE 2 | Image created in 2013 by Alexander Tarr, (currently assistant professor of geography at Worcester University), to represent the number and category of stakeholders participating in the LA Food Policy Council. Each square represents a participating organization, arrayed according to the work area they participated in for the LAFPC. Shown in the left column is the work area Institutional Good Food Purchasing, which was the organizational home of origin for the Good Food Purchasing Program.

The well-staffed, local government supported LAFPCgave rise to the Good Food Purchasing Program (the Program), as one of its many initiatives.

The Program was designed through an extensive two year process, involving multi-sector, interdisciplinary, and multi-stakeholder collaboration and an iterative review process by the designated team of the LAFPC, which included the Mayor's Senior Advisor on Food Policy. After arriving at a program design with LAFPC Working Group input, the policy and program was vetted by more than 100 local, state, and national public, private, and non-profit organizations through a due diligence process led by the Mayor's office in its role as LAFPC lead.

At the culmination of the design, development and review process, Mayor Villaraigosa issued an executive directive ordering all general funded city departments that purchased over $10,000 of food to adopt the Program. A motion in support of the directive was also adopted by the Los Angeles City Council on the same day. Consequently, on Food Day, October 24, 2012, the City of Los Angeles became the first institution in the country to take the early risk of embarking on the new Program. Just weeks later, the Los Angeles Unified School District (LAUSD)—which served 650,000 meals each day and is the largest food purchaser in Los Angeles—became the second institution to sign on to implementing the Good Food Purchasing Program.

The LAFPC built out the Program in detail, to guide data collection and implementation. It provided programmatic support in areas such as increasing supply chain transparency, data collection, record-keeping, menu design, bidding processes, and assessing suppliers' adherence to the five values.

Within 1 year, the Program adoption at LAUSD met with the success that its design was intended to promote: local sourcing of produce rose from an average of 10% per year to an average of 60% per year, redirecting USD 12 million to the local food economy. As a result, 150 new well-paid food chain jobs were created in L.A. County, including food processing, manufacturing and distribution. In the ensuing years, 160 truck drivers in LAUSD's supply chain received higher wages and improved working conditions.

Due to the immediate success of the Program at LA Unified School District, interest in adoption by other cities was piqued. In 2015 the Program was spun off from the LAFPC and became the program of the Center for Good Food Purchasing, which was established to advance the national expansion of the Program. The Program has since expanded significantly. As of June 2020, there are 49 institutions in 20 cities across the US enrolled in the Program in addition to LA, including New York, Chicago, Boston, San Francisco, Minneapolis and many others. These institutions collectively spend over $1 billion on food annually.

As a result of its contribution to advancing agroecology, the Program was recognized with an honorable mention for the Future Policy: Scaling Up Agroecology Award in 2018[8] by the World Future Council, the Food and Agriculture Organization of the United Nations (FAO), and IFOAM Organics International.

Stakeholders and Beneficiaries

The Center coordinates a network of national partners, local coalitions, food service directors, and elected officials across the country to implement and scale the Good Food Purchasing Program. In cities across the country, the Center works with a network of cross-sector partners at the national and local levels to expand the Program's reach and impact. Among the key national partners are the Food Chain Workers Alliance, Real Food Media and the HEAL Food Alliance.

Local, multi-sector coalitions help to ensure that Program adoption and implementation in a city or region reflects community priorities and complements existing work on the ground. Local coalitions help to recruit institutions, secure formal program adoption through policy, and influence public procurement processes to ensure that institutions and their vendors are held accountable to their policy commitments and that public contracts reflect community priorities.

The Program is implemented by food service directors of public institutions, such as school districts, hospitals, jails, and municipally operated concessions such as recreation centers, entertainment venues, and airports.

Primary beneficiaries are the low-income individuals, families and children served by public institutions such as schools, municipal programs, corrections and hospitals. One of the primary reasons the program targets public institutions is because these institutions play such a critical role in ensuring access to healthy food by low-income children, families, and communities of color, including seniors. For example, free-and-reduced price lunch[9] eligibility rates range from 65 to 85% in school districts enrolled in the Program, and as many as 90% of those are disadvantaged students of color.

Other beneficiaries of the Program who benefit from the additional economic support that the Program encourages include: (1) farm and food chain workers, a majority of whom are people of color, have extremely low incomes, are exposed on a daily basis to toxic pesticides, and lack access to safe drinking water due to groundwater contamination from agricultural runoff; and (2) small- to mid-sized producers practicing agroecological and high welfare farming and ranching, who struggle to compete with large, industrial producers in accessing institutional supply chains.

[8]Good Food Purchasing Program. FuturePolicy.org. Available online at: https://www.futurepolicy.org/healthy-ecosystems/los-angeles-good-food-purchasing-program/ (accessed June 17, 2020).

[9]The US National School Lunch Program. Available online at: *https://www.fns.usda.gov/nslp* (accessed June 17, 2020).

Purpose and Objectives

The Program's purpose is to harness the purchasing power of major institutions to encourage greater production of sustainably produced food, healthy eating, respect for workers' rights, humane treatment of animals and support for the local small business economy in order to achieve an economy of scale in a community oriented, "Good Food" system.

Methods and Modalities

The Program's metric-based, flexible framework (the Good Food Purchasing Standards) encourages large public institutions to measure and then make shifts in their food purchases. It is the first procurement model to support five core food system values—local economies, environmental sustainability, valued workforce, animal welfare and nutrition—in equal measure. By adopting the framework, food service institutions commit to improving their regional food system by implementing meaningful purchasing standards in all five value categories:

- Local Economies: The Good Food Purchasing Program (the Program) supports local small and mid-sized agricultural and food processing operations. The definition is based on a combination of farm size (based on revenue), farm ownership structure (family or cooperatively owned), and farm distance from the purchasing institution (based on driving distance). Farm sizes refer to USDA definitions.
- Environmental Sustainability: The Program requires institutions to source from producers that employ sustainable production systems that reduce or eliminate synthetic pesticides and fertilizers; avoid the use of hormones, routine antibiotics and genetic engineering; conserve and regenerate soil and water; protect and enhance wildlife habitats and biodiversity; and reduce on-farm energy and water consumption, food waste and greenhouse gas emissions; as well as to increase menu options that have lower carbon and water footprints. Examples of certifications include: Rainforest Alliance Certified, Seafood Watch, USDA Organic, etc.
- Valued Workforce: The Program promotes safe and healthy working conditions and fair compensation for all food chain workers and producers. The baseline is compliance with basic labor laws by the institution, vendor(s) and all suppliers. Examples of certifications or practices: union contract, worker-owned cooperative, Fair Trade Certified, Fair for Life, etc.
- Animal Welfare: The Program promotes healthy and humane care for farm animals. Examples of certifications in the Good Food Purchasing Standards include: USDA Organic, Certified Humane, Animal Welfare Approved etc.
- Nutrition: The Program promotes health and well-being by offering generous portions of vegetables, fruit, whole grains and minimally processed foods, while reducing salt, added sugars, saturated fats, and red meat consumption, and eliminating artificial additives. A 25-item checklist was initially developed with the L.A. County Department of Public Health,

and is aligned with national standards, such as the Healthy Hunger Free Kids Act.

The Center conducts the verification; scoring and recognition are central components of Program adoption by the institutions [for those familiar with LEED certification (Leadership in Energy and Environmental Design), the Program functions in an analogous fashion, and a comparison could be made between the Center's role vis the Program and the role of the US Green Building Council for LEED]. The verification process works in this way: when an institution adopts the Program, the Center works with them to collect in depth information about purchasing and food service practices, and rates the institution according to the rubric of the Center's copyrighted Standards. Each of the five value categories has a baseline standard, which indicates that the institution has met the Good Food Purchasing standards in at least 15% of its sourcing in each of the five values. Meeting even higher standards results in more points being awarded. The accumulation of points across all values is used to calculate and award a star rating. The baseline and higher standard purchasing criteria are set out in the Good Food Purchasing Standards, which are regularly reviewed and updated with a new version every 5 years. There are five status levels of a Good Food Provider (1–5 Stars) that correspond to a respective range of points. In order to achieve a Good Food Provider–5 Star level, the institution must achieve 25 or more points. After the first year, purchasers are expected to gradually increase the amount of Good Food that they purchase.

The expansion of the Good Food Purchasing Program is a highly collaborative, networked strategy. Cross-sector collaboratives of community, local policymakers, institutions, and value-chain partners exist in every city where the Center works. The local organizations who lead local Good Food Purchasing initiatives are deeply rooted in their communities, and while they represent a diverse range of interests, they participate in Program adoption at a selected array of local anchor institutions, recognizing this procurement strategy as a key economic lever for transforming the local food system toward one with an enduring commitment to the agroecological principles of economic equity, healthy equity, and environmental sustainability. The Center's staff works in close partnership with these communities to support community-driven efforts to use the Program as a tool to advance their local food system priorities.

Examples of the Local Partner Engagement

As of June 2020, the Center is actively engaged in 20 US cities, with a number of additional regions in the pipeline. While each city's Good Food Purchasing Program efforts are unique, a typical engagement involves dozens of local and national partners, interfacing with the Center and institutional partners all along the Good Food Purchasing journey. The following are illustrative examples from four cities.

Los Angeles

In Los Angeles, the LAFPC is now the local lead partner, serving as an accountability partner to enrolled city departments and the LAUSD. The LAFPC convenes local cross-sector stakeholders, builds broad support for the Program, identifies new institutions to recruit into the initiative, leads local efforts with partners, ensures a rigorous implementation of the Program by participating institutions, and maintains local relationships with public officials.

In Los Angeles, the Program's impacts continue to ripple throughout the city and region. The Program has helped redirect taxpayer dollars toward more values-aligned suppliers for receiving institutional food contracts. For example, due to successful organizing efforts led by the Food Chain Workers Alliance and a coalition of local advocates, the meat processor Tyson Foods was prevented from receiving a multimillion dollar chicken contract from the Los Angeles Unified School District due to their repeated egregious labor violations, as well as Tyson's environmental and animal welfare practices.

LA Unified School District currently purchases over $17 million in food from local growers and manufacturers. As of 2018, the school district was purchasing 96 percent of its chicken raised without routine antibiotics—just shy of the goal of 100 percent they set in 2014 as part of their Good Food Purchasing Program commitment and Urban School Food Alliance membership.

LAUSD has also promoted a valued workforce in its supply chain through the Program, contributing to the Teamsters Local 63 and Joint Council 42's efforts to secure union contracts for truck drivers and warehouse workers at a food distribution company. The Local and Joint Council were able to make the case for higher wages and workplace protections for 320 drivers and warehouse workers based on LAUSD's Good Food Purchasing Program commitment. These workers have seen their base salary increase by over 40 percent. Additionally, they are guaranteed raises over the next three years, have a grievance procedure, a voice with management, and a new pay incentive program.

Chicago

The Chicago Food Policy Action Council and a coalition of over 40 organizations organized a successful campaign that led to the adoption of the Program in the City of Chicago, the Chicago Parks District, and Chicago Public Schools in 2017. And with leadership from then-Cook County Board Commissioner Jesus "Chuy" Garcia and the County's Commission on Social Innovation, the county followed suit in 2018, making it the first county (a distinct municipality from a city) in the nation to adopt the Program. In Cook County, enthusiasm for the Program came in large part from those businesses, workers, consumers, and farmers that have long been marginalized in the food system. Under the Program, the County will incentivize contracts with minority- and women-owned businesses. In addition, the County is using the Program as a tool to connect with and accelerate other high priority equity initiatives, such as urban farmland preservation with community ownership, and transitioning publicly owned vacant lots to minority-owned social enterprises and public land trusts.

New York

The Mayor's Office of Food Policy supports implementation efforts by offering sustained leadership, convening agencies and key stakeholders through a task force structure and serving as a de-facto project manager for the City of New York's Good Food Purchasing engagement. Concurrently a coalition of ∼40 cross-sector organizations, led by Community Food Advocates, Food Chain Workers Alliance, and CUNY Urban Food Institute, meet regularly to coordinate their collaboration, the goal of which is to ensure the city's internal commitment to the five values is institutionalized through adoption of the Program, along with a Good Food Purchasing policy. The Mayor's office is also working to align the agency commitments with the community's priorities.

Austin

In February 2019, after a three-year pilot program, Austin Independent School District (AISD)—serving 75,000 meals per day on 129 campuses and managing a $13 million annual food budget—officially became the first school district in Texas to adopt the Good Food Purchasing Program. As a member of the Austin Good Food Purchasing Coalition, convened by the City of Austin's Office of Sustainability, AISD (along with two other Austin-based public institutions) was one of the first institutions outside of California to pilot the Program. Since 2016, the Center for Good Food Purchasing has worked with AISD to track and measure consistent improvement in their performance across the value categories. Expenditures on organic products tripled over the first 2 years in the Program. In 2018, AISD invested in dedicated staffing to help them obtain a four-star rating and earn their Good Food Provider status. Since then, AISD has made meaningful progress in implementing strategies to accelerate their good food purchases by releasing bids for bulk organic milk and grass-fed beef to bolster performance in environmental sustainability and animal welfare.

Aggregated Impact and Influence

Los Angeles (the first city to adopt the Program) is an example with the most longitudinal information. Since 2012, the Program has influenced ∼750,000 meals a day in L.A. City Departments and LAUSD, which alone serves over 600,000 students. In addition to the immediate impacts noted above, continuous improvement has been made in that district. For example, LAUSD's bread distributor had been sourcing out-of-state wheat for its USD 45–55 million annual servings of bread and rolls; due to participation in the Program the bread vendor changed its sourcing so that now, nearly all of the L.A. school district's bread and rolls are made from wheat grown on 44 Food Alliance-certified farms in California, milled in downtown L.A. These impacts extend beyond LAUSD as the same vendor, Gold Star Foods, now distributes these same products to over 550 schools across the western United States.

There has been a 15 per cent decrease in spending on meat by LAUSD due to implementing Meatless Mondays, which each week saves about 19.6 million gallons of water. From 2011 to 2017, LAUSD reduced purchases of all industrially-produced meat (beef, poultry and pork) by 32 percent, which led to reductions in their carbon and water footprint by 20 percent and 20.5 percent per meal, respectively, since the baseline year of 2012. The reduced carbon footprint translates to about 9 million kg of CO_2 emissions avoided per year—the equivalent to taking 1,930 cars off the road, and the water saved results in a total annual water savings of more than 1 billion gallons, enough water to fill 1,760 Olympic-sized swimming pools every year[10].

Leading the way, L.A. City Departments and LAUSD set an example that has since influenced many further areas in the U.S. As highlighted by the Union of Concerned Scientists in their 2017 report on the impacts of the Good Food Purchasing Program in Los Angeles, the "benefits of a better supply chain are amplified across institutions and regions."[11] Indeed, the recent calculations of the Center, based on over 10 years of data acquired from the institutions enrolled in the Program show combined totals across institutions of over $56,000,000 in supporting local economies, over $32,000,000 in supporting fair labor, over $20,000,000 toward meat raised without routine use of antibiotics, and an additional $10,000,000 supporting environmental sustainability.

Complementary Laws and Policies

In his Briefing Note 8 (April 2014), "The Power of Procurement: Public Purchasing in Realizing the Right to Food," UN Special Rapporteur Olivier De Schutter recognized that "Governments have few sources of leverage over increasingly globalized food systems—but public procurement is one of them. When sourcing food for schools, hospitals and public administrations, Governments have a rare opportunity to support more nutritious diets and more sustainable food systems in one fell swoop."

Procurement is also one of the recommended actions of category five of the Milan Urban Food Policy Pact, which calls for a review of "public procurement and trade policy aimed at facilitating food supply from short chains linking cities to secure a supply of healthy food, while also facilitating job access, fair production conditions and sustainable production for the most vulnerable producers and consumers, thereby using the potential of public procurement to help realize the right to food for all."[12]

The Good Food Purchasing Program is also consistent with the UN Sustainable Development Goals, and sustainable procurement goals of other organizations, as shown in **Table 1**.

The Future Policy 2018 Award

The systemically holistic Good Food Purchasing Program was favorably recognized in 2018 by the World Future Council, the Food and Agriculture Organization of the United Nations (FAO), and IFOAM Organics International. **Table 2** outlines their evaluation assessment and score.

[10] Reinhardt, S., and Kranti M. (2018). Purchasing Power: How Institutional "Good Food" Procurement Policies Can Shape a Food System That's Better for People and Planet (Union of Concerned Scientists). Available online at: *https://www.ucsusa.org/sites/default/files/attach/2017/11/purchasing-power-report-ucs-2017.pdf* (accessed June 17, 2020).

[11] Id.

[12] Available online at: http://www.milanurbanfoodpolicypact.org/text/ (accessed June 25, 2020).

TABLE 1 | The good food purchasing program and its alignment with sustainable development goals.

GFPP ALIGNMENT WITH SDGs	Local Economies	Environmental Sustainability	Valued Workforce	Animal Welfare	Health & Nutrition
GOOD FOOD PURCHASING PROGRAM	✓	✓	✓	✓	✓
C40 CITIES	✓	✓			✓
THE COOL FOOD PLEDGE		✓		✓	✓
MILAN URBAN FOOD POLICY PACT	✓	✓	✓		✓
EAT	✓	✓			✓
SUSTAINABLE DEVELOPMENT GOALS	✓	✓	✓		✓

TABLE 2 | Qualitative Future Policy Standard evaluation results (World Future Council).

Principle	Evidence and informant comment
Sustainable use YES	• Verifies commitment toward five categories of sustainability, incl. environmental. • Supports certifications such as USDA Organic. Reduces antibiotics & pesticides. • Promotes smaller ecological food footprint, e.g., local, seasonal, less meat, etc.
Equity YES	• Promotes respect for farmers, ranchers, fishfolks, etc. Before GFPP, every institution had 10–12 suppliers with serious labor violations—GFPP changes this. • Enhances livelihoods of food chain workers: women, migrants, indigenous, youth. • Promotes locally owned, small- to mid-sized farms, within 250 miles.
Precautionary approach YES	• Demands healthier food (a plant-based diet with some meat), prevents diseases. • Creates a demand for healthier food throughout life by school children. • Enhances relationships with local ecosystems; educates and raises awareness.
Participation YES	• Is a major outcome of a group led by the LAFPC, engaging 100+ stakeholders. • Transparent food supply chain and public accountability is its overall goal. • Center for Good Food Purchasing is accessible and prepares public reports.
Governance YES	• Stringent budget management, elaborate evaluation & transparent governance. • Center supports implementation (technical support) and monitoring (evaluation). • Creates opportunities for mid-size local ownership to access the supply chain.
Integration and interrelationship YES	• Promotes integration of social justice and environmental protection into all sectors of public policy, e.g., urban farmers now receive tax benefits. • Shows how to enact real change at local level by redirecting existing budgets.
Differentiation YES	• Levels the playing field: taxpayers' money is used to support fair working conditions. • Is adapted and uses the language of economy which is predominant in the U.S.

ACTIONABLE RECOMMENDATIONS AND CONCLUSIONS

Based on the Center's experience in working with local and national partners, the following key elements are instrumental in utilizing a procurement policy, such as the Good Food Purchasing Program, in creating a more agro-ecologically oriented food system on a regional scale:

- A collaborative, multi-sector coalition (like a food policy council) focused on a localized food system with shared values of community, equity, economic and environmental health

- Supply chain infrastructure that includes mission driven centers of aggregation, processing, and distribution (food hubs), dedicated to the same vision and goals of the collaborative
- Deeply invested, community informed local government leadership to connect the necessary dots within and across the many city and county agencies that intersect with food – which should include the workforce and economic development teams, in recognition that the food system is an economic one that responds to financial incentives and investments.

In order to accelerate the economic viability of an agro-ecologically oriented regional food system, an overarching goal should be developed to:

- Establish aggregate, quantifiable goals across the range of large anchor institutions (schools, hospitals, jails, recreational venues) in a region, to direct the combined purchasing power of the large anchor institutions toward increasing economic viability along a values based supply chain (such as the goals found in the Good Food Purchasing Program).

The procurement processes of large institutions allow them to obtain reasonable percentages of values-based food within their budgets, as conveyed to the food service or supply bidders through Requests for Proposals. The financial security of the long term, high volume contracts of schools and other large institutions is a de-risking opportunity for the supply chain.

If cities as centers of regional food change were to coordinate their public food procurement contracts with value based goals, the combined purchasing power could be the basis for a more equitable, community centered mid-scale food supply chain, operating alongside the more globalized supply chain in the way renewable energy operates alongside the prevailing energy fuel system.

A mid-tier[13] or community level system—one organized as a regional supply chain calibrated with value based purchasing policies with large scale commitments from public institutions—could support entrepreneurial responsiveness to the varied needs of a community.

- Cities and counties should adopt purchasing targets for all their large food service institutions that direct a meaningful percent of purchases to the public values of local economic support, fair wages and working conditions, and people and planetary health.
- Goals supporting local economies, sustainable production practices, fair labor practices, and nutritional health should be targeted and implemented with equivalent priority.
- Equity goals should be front and center, as shown in the Good Food policy resolutions of Cook County, Illinois[14], and should incorporate access to land and capital for historically dispossessed communities[15].
- City and county leaders should aggregate the institutional targets into regional targets. They should extend their reach beyond municipal and school food to include hospitals, military bases, jails and other publicly funded food programs available in each city. The aggregate dollars available to nurture a good food system, would be more than enough to make a difference in the regional food economy and in the well-being of their region.
- Those targets should be backed up with contractual commitments to producers and distributors.
- Develop and direct financial incentives to the anchor institutions to enable purchasing support for fair wage and climate friendly food production practices such as soil health. Incentives should include an increase in school meal reimbursements for the procurement of local, sustainable, fair, and humanely produced foods to provide all students access to nutritious, high-quality, local food, building on the pioneering local food incentive models established in Michigan[16], Oregon[17], and New York[18].

A system that serves community health, workers, and local businesses along those supply chains, can be a more resilient system in times of crisis. Healthy food, and the ability to make a fair living producing, picking, packing, and processing it, are essential to the equitable well-being of everyone who participates in the food system. The food system provides an essential good and service, and managing it in a way that is sustainable for the planet and people is a social, economic and environmental imperative.

AUTHOR CONTRIBUTIONS

PD and AD were responsible for the design, development, critical review, and implementation of the Program as the LAFPC Coordinator (AD), and the LAFPC Founder, Chair and Senior Advisor to the Mayor (PD). They since became co-founders of the Center for Good Food Purchasing, where AD is Executive Director. This report, which they wrote jointly, is their first person account of the program development, expansion, and implementation impacts.

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[13] Lyson, Thomas A., Stevenson, G. W., Welsh, R. (1998). *Food and the Mid-level Farm: Renewing an Agriculture of the Middle*. Cambridge: MIT Press.

[14] Cook County Board of Commissions. *Resolution To Adopt The Good Food Purchasing Policy. 14 May 2018*. Available online at: *https://gfpp.app.box.com/v/Resolution-CookCountyIllinois* (accessed June 17, 2020).

[15] Union of Concerned Scientists and Heal Food Alliance (2020). *Leveling the Fields: Creating Farming Opportunities for Black People, Indigenous People, and Other People of Color*. Cambridge.

[16] 10 Cents a Meal for Michigan's Kids & Farms. Available online at: *https://www.tencentsmichigan.org/* (accessed June 19, 2020).

[17] Kane, D., Kruse, S., Ratcliffe, M. M., Sobell, S. A., Tessman, N. (2011). *The Impact of Seven Cents*. Available online at: *https://ecotrust.org/media/7-Cents-Report_FINAL_110630.pdf* (accessed June 19, 2020).

[18] Farm-to-School. New York State. Available online at: *https://agriculture.ny.gov/farming/farm-school* (accessed June 19, 2020).

angelesgood-food-purchasing-program/, and also previously presented in part from the Center for Good Food Purchasing, https://goodfoodpurchasing.org/.

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EDITED BY
Franz-Theo Gottwald,
Humboldt University of Berlin, Germany

REVIEWED BY
Akbar Hossain,
Bangladesh Wheat and Maize Research Institute, Bangladesh
Eman A. Mahmoud,
Damietta University, Egypt

*CORRESPONDENCE
Vijay Singh Meena
vijayssac.bhu@gmail.com

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Long-term nutrient management in an intensive rice-wheat cropping system improves the quantities, qualities, and availability of soil sulfur

Sunita Kumari Meena[1,2], B. S. Dwivedi[1,3], Mahesh C. Meena[1], S. P. Datta[1], Vinod Kumar Singh[1,4], R. P. Mishra[5], Debashish Chakraborty[1], Abir Dey[1] and Vijay Singh Meena[6,7]*

[1]ICAR-Indian Agricultural Research Institute (IARI), New Delhi, India, [2]Department of Soil Science, Sugarcane Research Institute, Dr. Rajendra Prasad Central Agricultural University (RPCAU), Samastipur, Bihar, India, [3]ICAR-National Bureau of Soil Survey and Land Use Planning (NBSS and LUP), Nagpur, Maharashtra, India, [4]ICAR-Central Research Institute for Dryland Agriculture (CRIDA), Hyderabad, Telangana, India, [5]ICAR-Indian Institute of Farming Systems Research (IIFSR), Uttar Pradesh, Modipuram, India, [6]ICAR-Vivekananda Parvatiya Krishi Anusandhan Sansthan (VPKAS), Almora, Uttarakhand, India, [7]CIMMYT-Borlaug Institute for South Asia (BISA), Samastipur, Bihar, India

In the last few decades, the deficiency of sulfur (S) has been noticed in the agricultural soils of India. Meanwhile, researchers reported that S plays a significant role in the productivity of the rice-wheat cropping system (RWCS). For the quantification of S response, a long-term field experiment was started at the Indian Council of Agricultural Research-Indian Institute of Farming Systems Research (ICAR-IIFSR), Modipuram, India. In total, 7 nutrient supply options were applied, i.e., organic, mineral fertilizer in the combination of integrated plant nutrition system (IPNS), and IPNS + berseem (B)/IPNS + cowpea (C) in the S availability of the soil in the RWCS. The results showed that the highest contribution in S availability by the total S (39%) is followed by the organic S (35%), sodium bicarbonate extractable sulfur ($NaHCO_3$-ES; 7%), heat-soluble sulfur (SS; 7%), water-soluble sulfur (WSS; 4%), available S (4%), and inorganic S (4%) under different long-term nutrient supply options of RWCS. The continuous application of organic fertilizer and various IPNS options, such as the inclusion of pulses, significantly improved all S fractions in the soil and also offers an additional benefit in terms of sustainability of production and soil health as compared to the inorganic fertilizer fields. Overall, the results showed that IPNS showed its superiority over the rest of the treatment. The results also supported that the inclusion of pulses gives a further gain in terms of sulfur availability in soil systems under RWCS.

KEYWORDS
nutrient supply options, sulfur, nutrient availability, mineral fertilizer, organic manure

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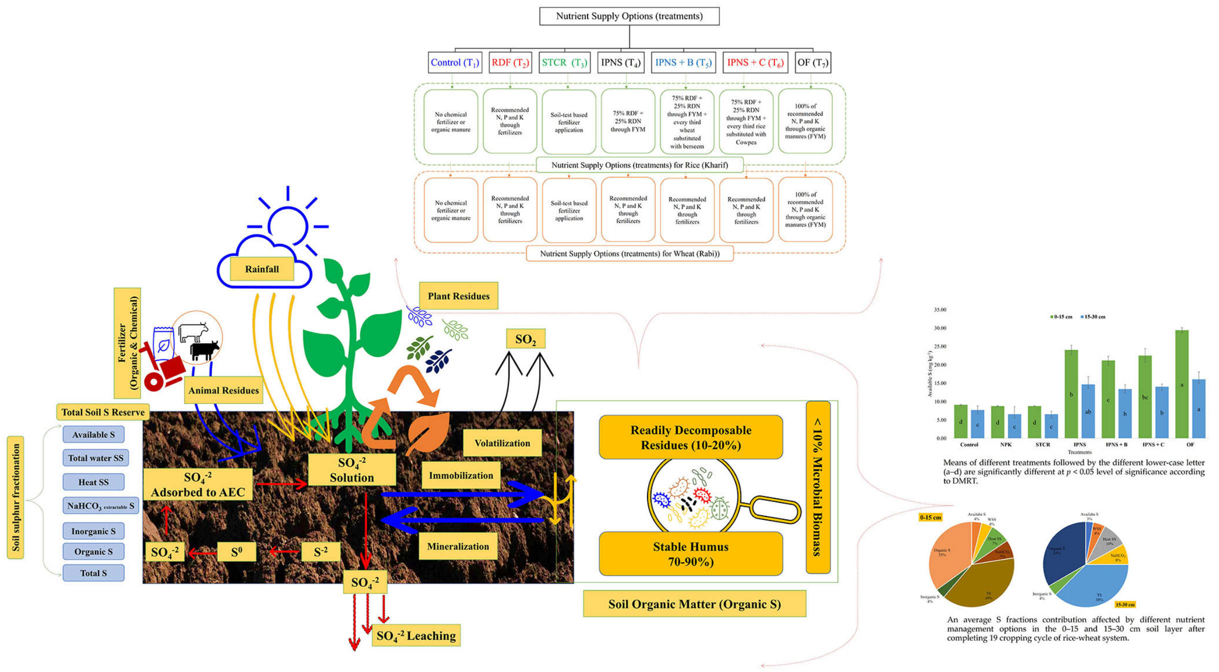

GRAPHICAL ABSTRACT
Graphical representation of soil sulphur availability impacted by different nutrient supply options.

Introduction

To attain UN Sustainable Development Goals (UNSDGs) globally, all nations have adopted these targets. To feed the rapidly growing global population, a sustainable food production system is required for confirming the overall development of society (Woolston, 2020). Similarly, sustainable management of the agroecosystem plays a significant role in attaining nutrition security (Singh et al., 2020; Dubey et al., 2021; Rakshit et al., 2022). Sustainable agriculture is also a decisive factor for society in developing nations (www.fao.org). Meanwhile, some of the agricultural activities are negatively affected, such as indiscriminate input use, intensive tillage, and puddled transplanted rice (Eisenstein, 2020).

Nowadays, researchers are giving more emphasis to higher productivity to feed the population with limited resources (Elferink and Schierhorn, 2016). As reported by the Food and Agricultural Organization of the United Nations (FAO), food production must be doubled by the year 2050 to feed a global population (http://www.fao.org) (Food and Agricultural Organization of the United Nations (FAO), 2009). Judicious application of S plays a major role in the growth and development of crops (Figure 1).

Many researchers reported that the S has a significant role in crop production (Jamal et al., 2010; Nazar et al., 2011; Sahota, 2012; Kopriva et al., 2019; Zenda et al., 2021). Sulfur is gaining considerable importance for enhancing crop yields and quality of production in the context of Indian agriculture. Tiwari and Gupta (2006) reported a large gap between the removal (≈1.26 Mt/year) and replacement (0.76 Mt/year) of sulfur in India. Continued depletion of native reserves of S during post-green revolution period has led to its deficiency in many regions of the country. Since the last two decades, S deficiency has been reported globally (Scherer, 2009; Sahota, 2012; Kopriva et al., 2019). Approximately 46% of agricultural soils of India observed S deficiency, and out of them, 30% of soils are potentially deficient (Satyanarayana and Tewatia, 2009).

Worldwide long-term field experiments have been considered as valuable devices for providing information on productivity, profitability, and soil sustainability (Singh et al., 2000; Borase et al., 2020; Sandhu et al., 2020; Dhawan et al., 2021; Singh and Saini, 2021). Nevertheless, knowledge of

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Abbreviations: IPNS, integrated plant nutrition system; IPNS + B, IPNS + berseem; IPNS + C, IPNS + cowpea; STCR, soil test crop response; RDF, recommended dose of fertilizer; OF, organic farming; NPK, nitrogen, phosphorous, potassium; S, sulfur, UNSDG, UN Sustainable Development Goals; RBD, Randomized Block Design, FYM, farmyard manure; WSS, water-soluble sulfur; Heat SS, heat soluble sulfur; $NaHCO_3$-ES, sodium bicarbonate extractable sulfur; inorganic S, inorganic sulfur; organic S, organic sulfur; total S, total sulfur.

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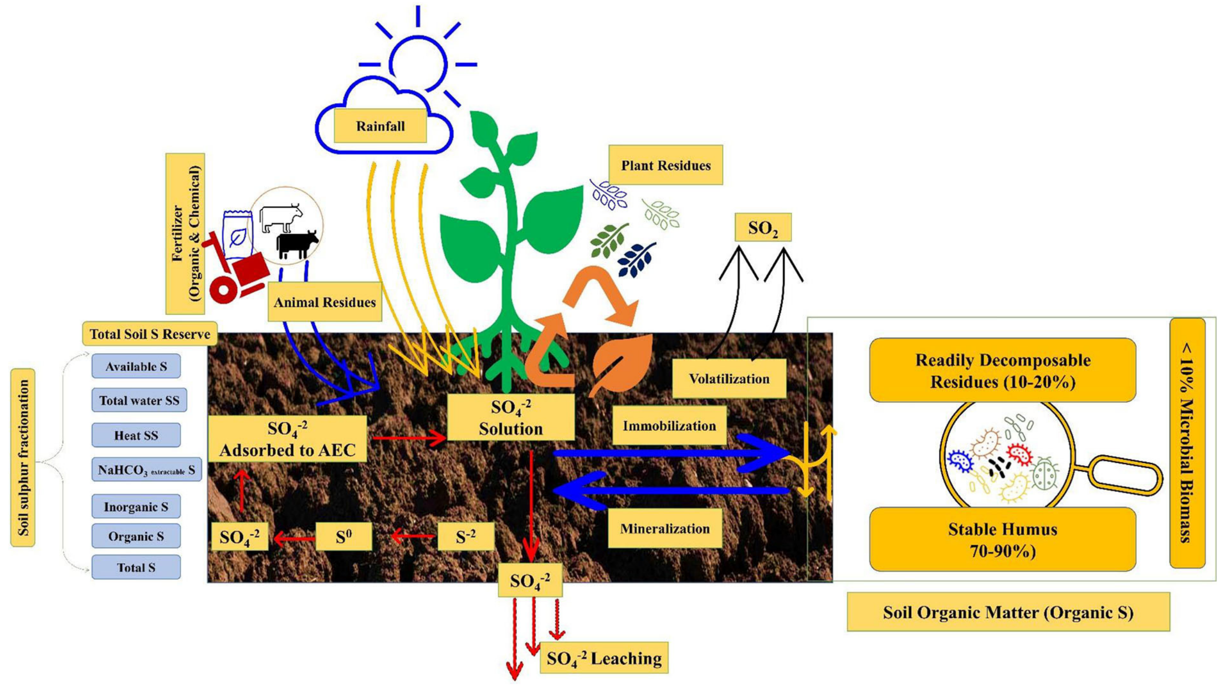

FIGURE 1
Sulfur availability in soils: (i) soil organic matter quantity and quality, (ii) crop selection and cropping system design, (iii) and (iv) biological and biochemical mineralization rates. In addition to soil test S concentrations, these factors should be considered when making fertility recommendations.

various forms of S is of much relevance in assessing its long-run use under field conditions.

The supposition set for our study was that the accumulation of different fractions of sulfur might be affected by the various integrated plant nutrition system (IPNS) options in the rice-wheat cropping system (RWCS). To test this hypothesis, the aims of this study were (i) to quantify the IPNS and soil depths on sulfur pools and (ii) to assess the best nutrient supply options and quantitative sulfur status and relationship as compared to unfertilized plot in the long-run under RWCS.

Materials and methods

Site descriptions

The ongoing long-term field experiment (starting year 1998) site of the Indian Council of Agricultural Research-Indian Institute of Farming Systems Research (ICAR-IIFSR) (29°4'N, 77°46'E, 237 m above sea level) was selected (Figure 2). The average monthly minimum (7.2°C) and maximum (20.1°C) temperatures in January and corresponding minimum (24.2°C) and maximum (39.8°C) temperatures in May with an annual rainfall of 823 mm.

Treatments and experimental design

The long-term cropping system experiment involving different nutrient supply options under RWCS is shown in Table 1. The experiment was conducted in large plots (individual plot area 1,000 m^2). All treatments were a randomized block design (RBD) and had four replications (Meena et al., 2022). A total of seven nutrient supply option treatments were imposed in the long-term cropping system experiment as T1: control, i.e., no chemical fertilizer or organic manure; T2: recommended fertilizer dose to rice and wheat; T3: soil-test-based fertilizer application in both crops; T4: 75% of recommended N, P, and K through fertilizers + 25% substitution of recommended N through farmyard manure (FYM) in rice and recommended dose of fertilizer (RDF) in wheat crop; T5: 75% of recommended N, P, and K through fertilizers + 25% substitution of recommended N through FYM + every third wheat substituted with berseem (B) for rice and RDF for the wheat crop; T6: 75% of recommended N, P, and K through fertilizers + 25% substitution of recommended N through FYM + every third rice substituted with cowpea (C) for rice and RDF for the wheat crop; and T7: 100% of recommended N, P, and K through organic manures (FYM) in both crops.

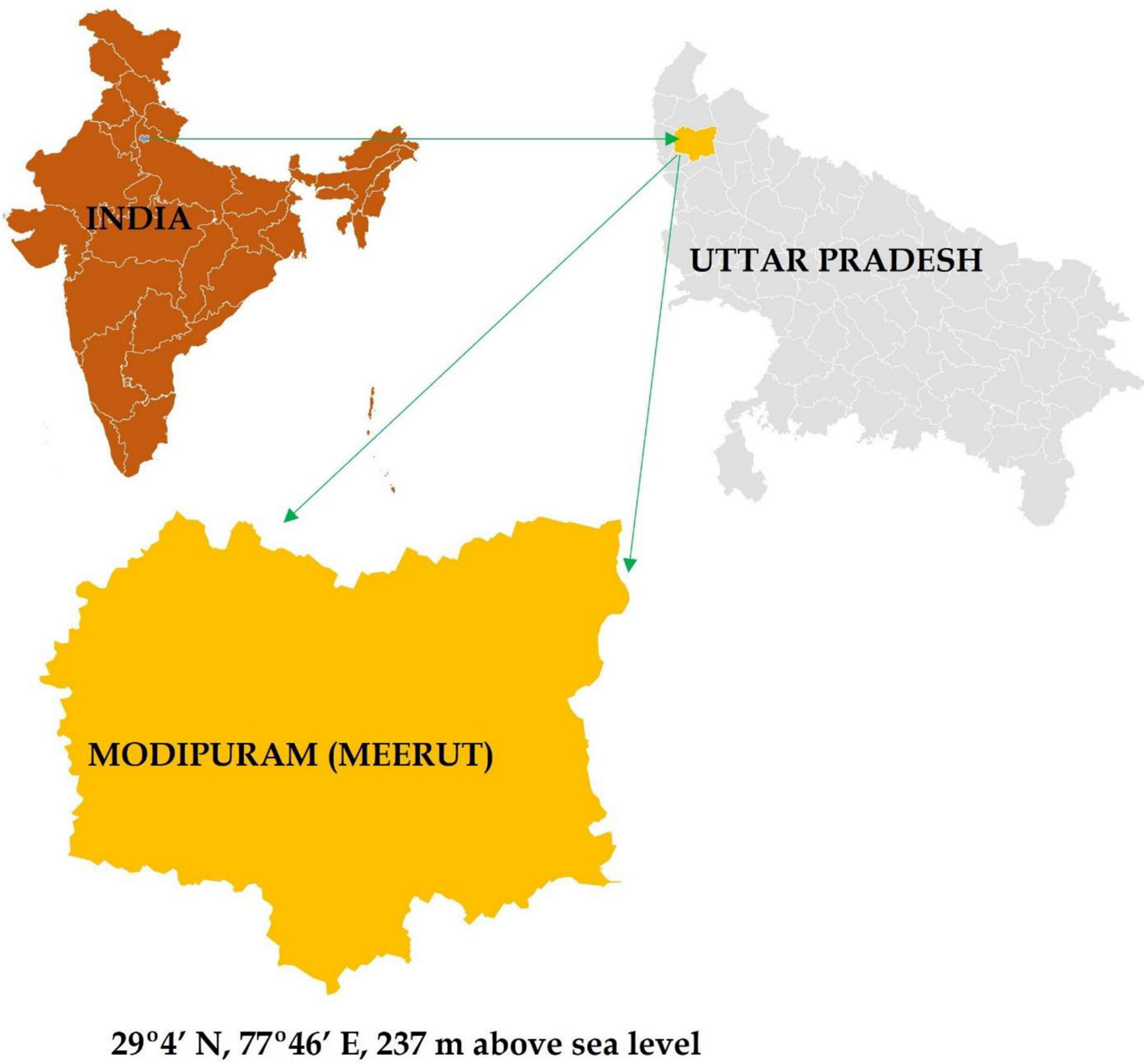

FIGURE 2
Experimental site of long-term rice-wheat cropping system (RWCS).

Soil and data analysis

Soil available and water-soluble sulfur were determined using $CaCl_2$ and NaCl methods, respectively (Chesnin and Yien, 1950; Williams and Steinbergs, 1959). Heat soluble sulfur was determined with 1% NaCl (Williams and Steinbergs, 1959). Sodium bicarbonate extractable sulfur ($NaHCO_3$-ES) was determined with 0.5 M $NaHCO_3$ at a pH of 8.5 (Kilmer and Nearpass, 1960), inorganic and organic S was determined with 0.01 M $CaCl_2$ (Williams and Steinbergs, 1959), and total S concentration was determined by Tabatabai and Bremner (1972), followed by the turbidimetric method of Chesnin and Yien (1950) at 420 nm wavelength by spectrophotometer.

Statistical analysis

The generated data were processed for analysis of variance (ANOVA), and Duncan's multiple range test (DMRT) was used to compare the differences between the means using as applicable to RBD to assess differences among the treatment means as described by Gomez and Gomez (1984). Correlation

TABLE 1 Experimental setup and treatments details for different nutrient supply options.

Treatment	Treatment details		
	Code	Kharif (rice)	Rabi (wheat)
T_1	Control	Not applied	Not applied
T_2	NPK	RDF through fertilizer	RDF through fertilizers
T_3	STCR	Fertilizer application based on soil testing results	Fertilizer application based on soil testing results
T_4	IPNS	75% RDF + 25% substitution of recommended N through FYM	RDF through fertilizer
T_5	IPNS+B	75% RDF + 25% substitution of RDN through FYM + every third rabi crop substituted with berseem	RDF through fertilizer
T_6	IPNS+C	75% RDF + 25% substitution of recommended N through FYM + every third kharif crop substituted with cowpea	RDF through fertilizer
T_7	OF	100% RDF through organic manure	100% RDF through organic manure

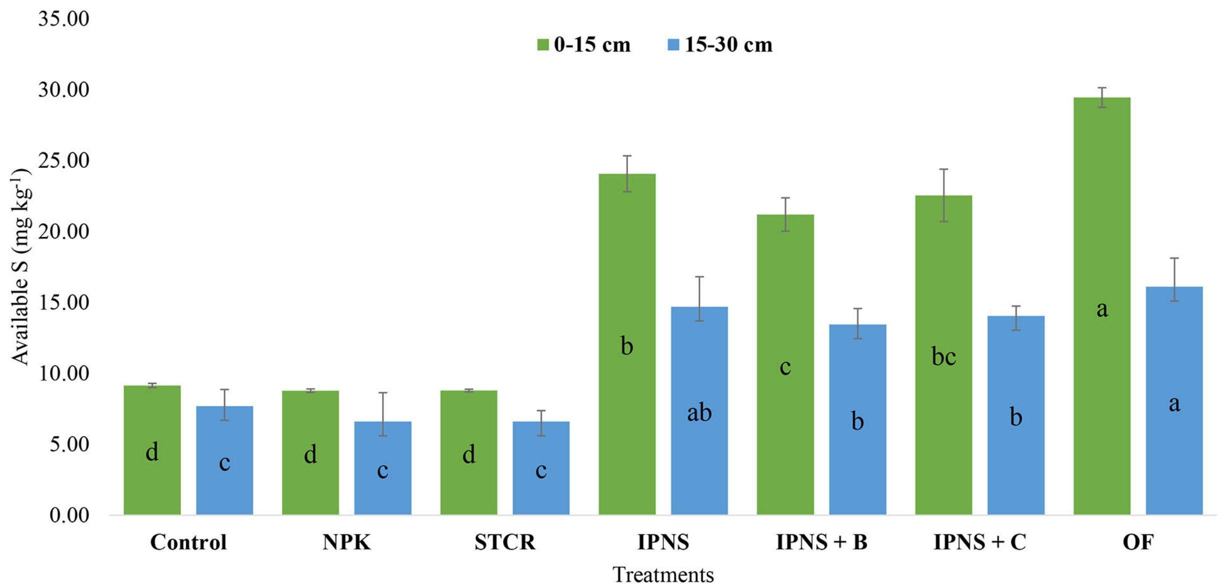

FIGURE 3
Effect of long-term fertilization on soil available S in the 0–15 and 15–30 cm soil layer of rice-wheat cropping system (RWCS). Means of different treatments followed by the different lower-case letters **(a–d)** are significantly different at $p < 0.05$ levels of significance according to Duncan's multiple range test (DMRT).

coefficients were computed using the SPSS program (SPSS version 16) (SPSS 1990).

Results and discussion

Impact on soil available sulfur

The results revealed that the available S significantly varied among the different treatment combinations over the RWCS (Figure 3). It varied from 8.80 to 29.40 and 6.60 to 16.10 mg S kg^{-1} in the 0–15 and 15–30 cm soil depths, respectively. A significantly greater amount of available S in the surface and subsurface soil (0–15 and 15–30 cm) was maintained with organic farming (OF) management over the rest of the treatment combination (Figure 3). The build-up values of available S in the 0–15 and 15–30 cm depths were 29.10 and 16.10 mg S kg^{-1} in plots' OF management practices, respectively, against 8.80 and 6.60 mg S kg^{-1} in both soil test crop response (STCR)- and nitrogen, phosphorous, potassium (NPK)-treated plots, respectively. The available S was increased by ≈30 and 41% in the 0–15 and 15–30 cm soil depths in plots receiving OF management practices, respectively, over the STCR and NPK plots. The available S in the 0–15 cm depth was recorded in the following order: OF (29.40 mg S kg^{-1}) > IPNS (24.10 mg S kg^{-1}) > IPNS + C (22.60 mg S kg^{-1}) > IPNS + B (21.20 mg S

TABLE 2 Impact of long-term integrated plant nutrition system (IPNS) options on soil sulfur fractions in the 0–15 cm soil layer of rice-wheat cropping system (RWCS).

Treatment	WSS	Heat SS	$NaHCO_3$ -ES	Total S	Inorganic S	Organic S
	———————————-mg S kg^{-1}					
Control	10.64 ± 0.44^{f}	20.93 ± 0.65^{f}	27.91 ± 0.72^{g}	150.84 ± 4.45^{f}	9.77 ± 0.61^{g}	141.07 ± 4.97^{f}
NPK	15.12 ± 0.12^{e}	31.47 ± 1.94^{e}	28.72 ± 0.56^{f}	162.98 ± 3.74^{e}	12.97 ± 0.26^{e}	150.01 ± 3.92^{e}
STCR	15.98 ± 0.07^{d}	32.85 ± 1.66^{e}	29.66 ± 0.60^{e}	167.00 ± 7.00^{e}	12.10 ± 0.19^{f}	150.68 ± 4.84^{e}
IPNS	19.63 ± 0.09^{c}	37.87 ± 0.75^{d}	32.33 ± 0.60^{d}	179.00 ± 4.88^{d}	17.41 ± 0.12^{d}	162.03 ± 4.22^{d}
IPNS + B	23.94 ± 0.05^{b}	40.41 ± 1.64^{c}	33.13 ± 0.28^{c}	195.01 ± 4.10^{c}	22.10 ± 0.38^{c}	172.61 ± 4.03^{c}
IPNS + C	24.13 ± 0.11^{b}	42.74 ± 1.82^{b}	36.85 ± 0.64^{b}	208.00 ± 4.01^{b}	22.98 ± 0.21^{b}	185.25 ± 7.15^{b}
OF	29.36 ± 0.25^{a}	45.75 ± 0.58^{a}	39.69 ± 0.57^{a}	220.04 ± 6.90^{a}	25.98 ± 0.23^{a}	194.07 ± 6.86^{a}

Means of different treatments followed by the different lower-case letters (a–g) are significantly different at $p < 0.05$ level of significance according to Duncan's multiple range test (DMRT).

TABLE 3 Impact of long-term integrated plant nutrition system (IPNS) options on soil sulfur fractions in the 15–30 cm soil layers of rice-wheat system.

Treatment	WSS	Heat SS	$NaHCO_3$ -ES	Total S	Inorganic S	Organic S
	———————————-mg S kg^{-1}					
Control	10.67 ± 1.17^{d}	29.03 ± 1.69^{f}	27.08 ± 2.45^{e}	119.80 ± 2.31^{e}	8.97 ± 0.63^{e}	110.83 ± 2.91^{e}
NPK	13.85 ± 2.04^{c}	32.56 ± 1.54^{e}	28.93 ± 1.20^{de}	121.81 ± 2.17^{e}	11.51 ± 0.94^{de}	110.30 ± 3.06^{e}
STCR	15.30 ± 0.78^{c}	34.90 ± 1.05^{d}	29.50 ± 0.50^{cd}	126.00 ± 8.30^{e}	12.10 ± 2.90^{d}	112.47 ± 3.16^{e}
IPNS	19.60 ± 2.12^{b}	38.50 ± 1.23^{c}	31.26 ± 1.64^{c}	143.01 ± 3.34^{d}	15.00 ± 1.46^{c}	128.02 ± 3.47^{d}
IPNS + B	20.44 ± 1.12^{b}	40.71 ± 1.62^{b}	31.01 ± 1.59^{cd}	156.00 ± 2.99^{c}	19.50 ± 1.69^{b}	136.71 ± 5.60^{c}
IPNS + C	20.66 ± 0.69^{b}	42.25 ± 1.41^{b}	34.76 ± 1.17^{b}	176.29 ± 4.67^{b}	21.72 ± 2.03^{ab}	154.57 ± 5.39^{b}
OF	24.11 ± 2.03^{a}	48.26 ± 1.61^{a}	36.89 ± 1.31^{a}	193.11 ± 9.21^{a}	24.39 ± 2.50^{a}	168.72 ± 7.10^{a}

Means of different treatments followed by the different lower-case letters (a–f) are significantly different at $p < 0.05$ level of significance according to Duncan's multiple range test (DMRT).

kg^{-1}) > control (9.10 mg S kg^{-1}) > STCR (8.80 mg S kg^{-1}) ≥ NPK (8.80 mg S kg^{-1}), and a similar trend was also observed in subsurface soils (Figure 3). The results clearly specify that the integrated use of nutrients has a constructive effect on soil available sulfur, which corresponds to the results presented by other authors (Soaud et al., 2011; Turan et al., 2013; Shi et al., 2016).

Impact on water-soluble sulfur

The results indicated that the concentration of WSS significantly varied among the different treatment combinations (Tables 2, 3). Significantly highest WSS was witnessed in plots receiving OF 29.36 (0–15 cm) and 24.11 mg S kg^{-1} (15–30 cm) soil depths. It was ≈36 and 44% significantly higher as compared to unfertilized control plots under both 0–15 and 15–30 cm soil depths, respectively. In the case of surface soil (0–15 cm soil depth), WSS ranged from 10.60 to 29.36 mg S kg^{-1} under different long-term nutrient supply options in the RWCS. The maximum WSS was recorded with OF-treated plots (29.36 mg S kg^{-1}) followed by the IPNS + C (24.13 mg S kg^{-1}), IPNS + B (23.94 mg S kg^{-1}), IPNS (19.63 mg S kg^{-1}), STCR (15.98 mg S kg^{-1}), and NPK (15.12 mg S kg^{-1}) plots, and the lowest WSS (10.64 mg S kg^{-1}) was recorded with unfertilized control plots.

Nevertheless, in the case of subsurface soil (15–30 cm soil depth), it ranged from 10.67 to 24.11 mg S kg^{-1} among the different nutrient management practices. The amount of WSS in the 15–30 cm soil layer was ∼8% lower as compared to surface soil. Significantly highest amount of WSS was recorded in the OF (24.11 mg S kg^{-1}) and the rest of the treatment combination was observed in the following order: IPNS + C (20.66 mg S kg^{-1}), IPNS + B (20.44 mg S kg^{-1}), IPNS (19.60 mg S kg^{-1}), STCR (15.30 mg S kg^{-1}), NPK (13.85 mg S kg^{-1}), and control (10.67 mg S kg^{-1}) plots (Tables 2, 3). The significantly higher content of water-soluble sulfur fraction with the integrated use of fertilizer and manure may be attributed to higher microorganisms in different treatment combinations that resulted in mineralization of organic sulfur to available sulfur (Dutta et al., 2013). Correspondingly, the integrated use of mineral fertilizers might have improved soil nutrient availability (Latare et al., 2014).

Impact on heat soluble sulfur

The results showed that the heat SS content of the soil under different treatments varied from 20.93 to 45.75 mg S kg^{-1} in surface soil and from 29.03 to 48.26 mg S kg^{-1} in sub-surface soil (Tables 2, 3). OF maintained higher heat SS (45.75 mg S kg^{-1}) followed by IPNS + C (42.74 mg S kg^{-1}), IPNS + B (40.41 mg S kg^{-1}), IPNS (37.87 mg S kg^{-1}), STCR (32.85 mg S kg^{-1}), NPK (31.47 mg S kg^{-1}), and unfertilized control (20.93 mg S kg^{-1}) plots in surface soil (0–15 cm). Meanwhile, in case of subsurface soil (15–30 cm), significant highest heat SS was reported with OF (48.26 mg S kg^{-1}) followed by IPNS + C (42.25 mg S kg^{-1}), IPNS + B (40.71 mg S kg^{-1}), IPNS (38.50 mg S kg^{-1}), STCR (34.90 mg S kg^{-1}), NPK (32.56 mg S kg^{-1}), and unfertilized control (29.03 mg S kg^{-1}). The plot receiving OF management practices showed its significant superiority by ∼ 54 and 40% as compared to control plot. Nevertheless, the levels of heat SS content were lower in surface than subsurface soils (Tables 2, 3). Application of IPNS increased heat soluble sulfur fraction as compared to control (no fertilizer application), which was released with heat treatment (Bediger et al., 1985; Dutta et al., 2013).

Impact on $NaHCO_3$-ES

Data revealed that the $NaHCO_3$-ES concentration was significantly highest under OF at 39.69 and 36.89 mg S kg^{-1} in the 0–15 and 15–30 cm soil depths, respectively (Tables 2, 3). The significant variation among different treatments was also noticed in both soil depths. In surface soil, the concentration of $NaHCO_3$-ES was observed in following order: OF (39.69 mg S kg^{-1}) > IPNS + C (36.85 mg S kg^{-1}) > IPNS + B (33.13 mg S kg^{-1}) > IPNS (32.33 mg S kg^{-1}) > STCR (29.66 mg S kg^{-1}) > NPK (28.72 mg S kg^{-1}) > unfertilized control (27.91 mg S kg^{-1}) under RWCS over the period. Similarly, the 15–30 cm soil depth significantly varied from 27.08 to 36.89 mg S kg^{-1} among different treatment combinations (Tables 2, 3). The maximum $NaHCO_3$-ES was recorded in OF-treated plots (36.89 mg S kg^{-1}) followed by IPNS + C (34.76 mg S kg^{-1}) > IPNS (31.26 mg S kg^{-1}) > IPNS + B (31.01 mg S kg^{-1}) > STCR (29.50 mg S kg^{-1}) > NPK (28.93 mg S kg^{-1}) > unfertilized control (27.08 mg S kg^{-1}) treatments. Both soil depth treatments with OF showed significant superiority over the rest of the treatment combinations under RWCS over the period (Tables 2, 3). The significantly higher concentrations of $NaHCO_3$-ES were found in the treated plot as compared to the unfertilized plot (Dutta et al., 2013).

Impact on inorganic sulfur

A significantly greater amount of inorganic S was maintained in OF treatment over the rest of the treatment combination in both surface and subsurface soil layers (Tables 2, 3). The build-up of inorganic S ranged from 25.98 to 24.39 mg S kg^{-1} in plots receiving OF against 9.77 and 8.97 mg S kg^{-1} in unfertilized control plots in surface (0–15 cm) and subsurface (15–30 cm) soil depths, respectively. The inorganic S was increased by ∼33 and 37% in plots receiving OF in the 0–15 and 15–30 cm soil depths, respectively, over unfertilized plots. In the case of surface soil (0–15 cm soil depth), inorganic S ranged from 9.77 to 25.98 mg S kg^{-1} under different nutrient supply options in the RWCS over the periods. The maximum inorganic S was recorded with OF-treated plots (25.98 mg S kg^{-1}) followed by the IPNS + C (22.98 mg S kg^{-1}), IPNS + B (22.10 mg S kg^{-1}), IPNS (17.41 mg S kg^{-1}), NPK (12.97 mg S kg^{-1}), and STCR (12.10 mg S kg^{-1}), and the lowest inorganic S (9.77 mg S kg^{-1}) was recorded with unfertilized control plot (Tables 2, 3).

Nevertheless, in case of subsurface soil (15–30 cm soil depth), it ranged from 8.97 to 24.39 mg S kg^{-1} among IPNS options. The amount of inorganic S in the 15–30 cm soil layer was ∼10% lower as compared to surface soil. The significantly highest amount of inorganic S was recorded in the OF (24.39 mg S kg^{-1}), and the rest of the treatment combination was observed in the following order: IPNS + C > IPNS + B > IPNS > STCR > NPK > unfertilized control plots under RWCS over the periods (Tables 2, 3). A similar trend like WSS was reported in the case of inorganic sulfur, and it might be due to the long-term effect of nutrient supply options that contribute to total sulfur, and in the form of mineralization, it will be available to crops. Kumar et al. (2011) also reported that higher inorganic sulfur was reported in IPNS as compared to control.

Impact on organic sulfur

Organic S is the second largest fraction contribution among all sulfur pools after total sulfur (Tables 2, 3). The results revealed that the concentration of organic S significantly varied among the different treatment options over the periods. It ranged from 141.07 to 194.07 mg S kg^{-1}. It was also observed that the organic S was significantly influenced by different nutrient supply options over the periods, and it was reported in following order: OF (197.07 mg S kg^{-1}) > IPNS + C (185.25 mg S kg^{-1}) > IPNS + B (172.61 mg S kg^{-1}) > IPNS (162.03 mg S kg^{-1}) > STCR (150.68 mg S kg^{-1}) > NPK (150.01 mg S kg^{-1}) > unfertilized control (141.07 mg S kg^{-1}) plots. Similarly, the 15–30 cm soil depth significantly varied from 110.83 to 168.72 mg S kg^{-1} among different treatment combinations (Tables 2, 3). A similar trend was observed in the subsurface (15–30 cm) soil depth. However, the levels of organic S content were lower (−12%) in the subsurface than in the surface soil layer. The organic sulfur is the largest pool among the different pools of sulfur, which accounted for ∼90–95% of total sulfur. The lower quantity of organic sulfur in the unfertilized plots might be due to its mining to meet the RWCS supplies (Rongzhong et al., 2010; Dutta et al., 2013).

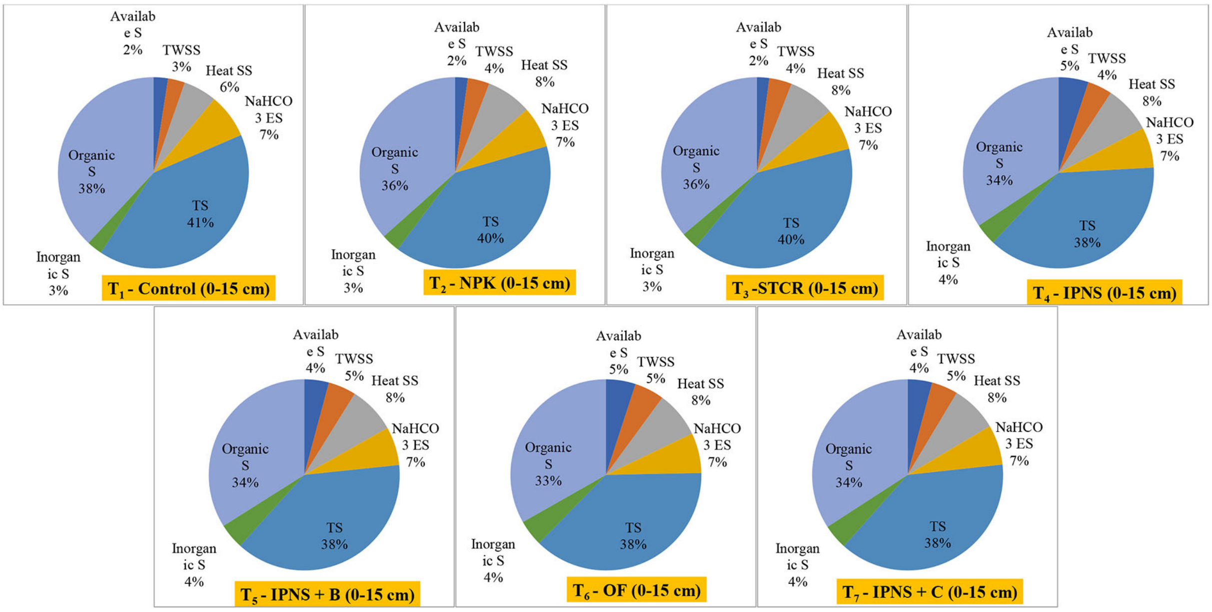

FIGURE 4
Effect of long-term nutrient supply on soil sulfur fractions contribution in the 0–15 cm soil layer of rice-wheat cropping system (RWCS).

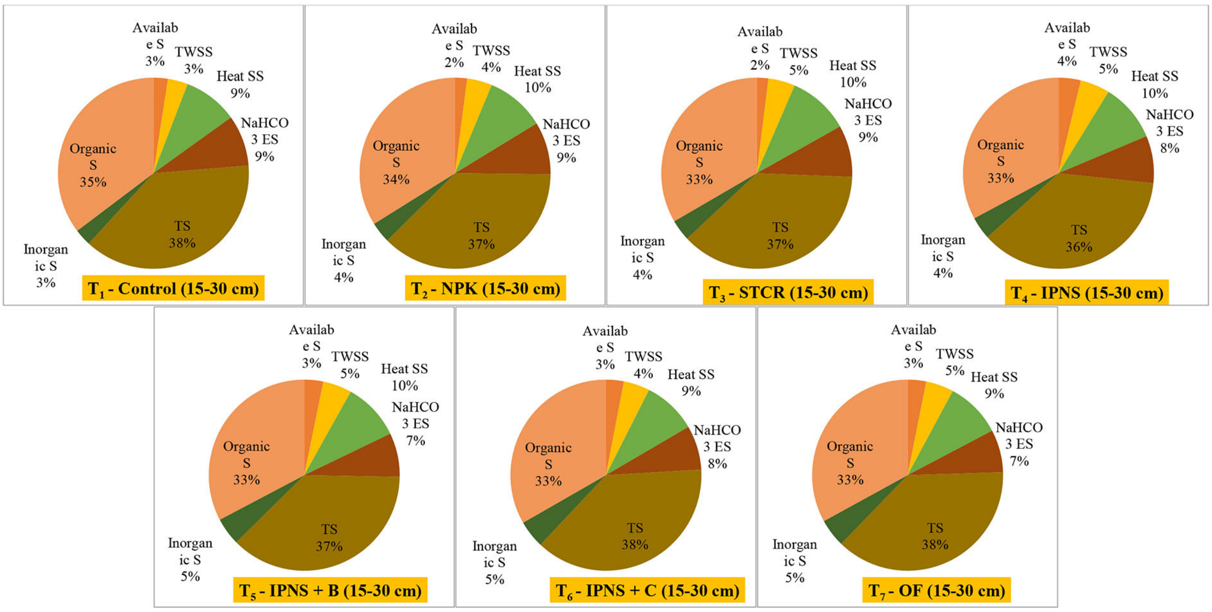

FIGURE 5
Effect of long-term nutrient supply on soil sulfur fractions contribution in the 15–30 cm soil layer of rice-wheat cropping system (RWCS).

Impact on total sulfur

The plot with OF indicated its significant superiority over the rest of the treatment combination (Tables 2, 3). Data indicated that the total S significantly highest 0–15 cm (220.04 mg S kg^{-1}) and 15–30 cm (193.11 mg S kg^{-1}) was observed in OF-receiving plot. Total S fractions significantly varied from 150.84 to 220.04 mg S kg^{-1} among different IPNS options in surface soil. Data affirmed that in surface soil (0–15 cm depth), total S fraction was

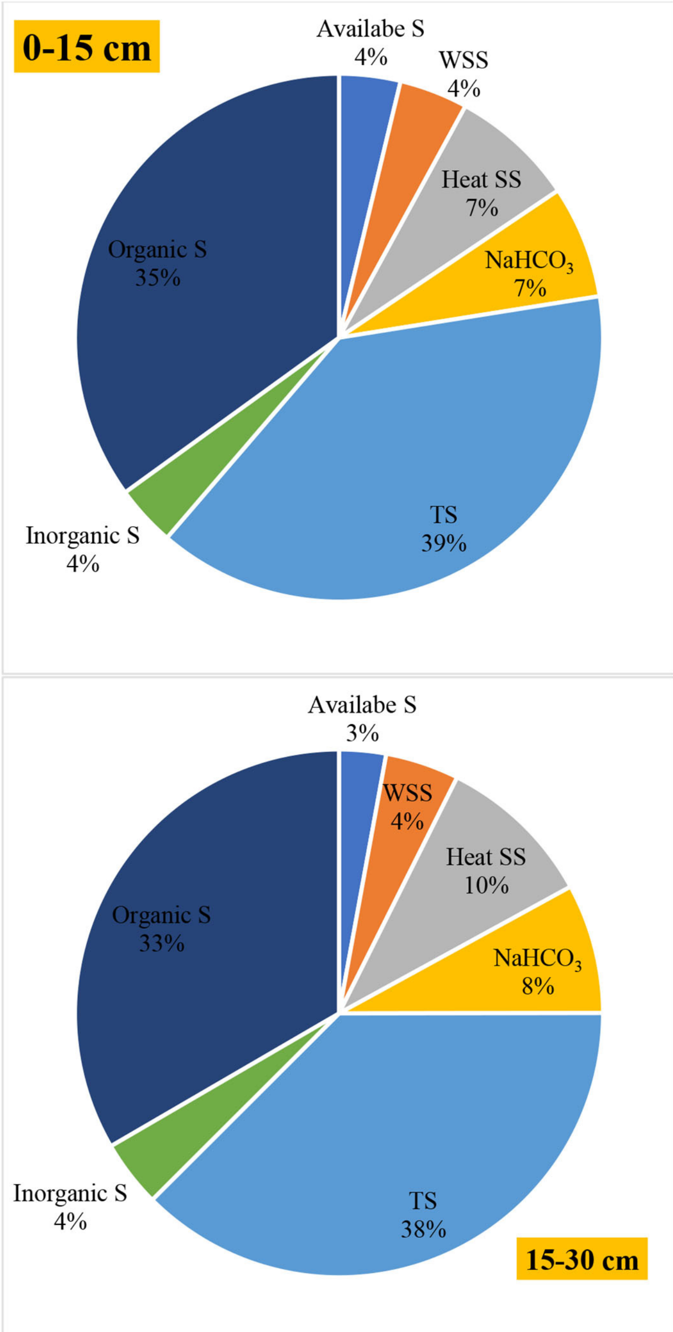

FIGURE 6
Effects of long-term nutrient supply on soil sulfur fraction contributions in the 0–15 and 15–30 cm soil layers of rice-wheat cropping system (RWCS).

observed in the following order: OF (220.04 mg S kg^{-1}) > IPNS + C (208 mg S kg^{-1}) > IPNS + B (195.01 mg S kg^{-1}) > IPNS (179 mg S kg^{-1}) > STCR (167 mg S kg^{-1}) > NPK (162.98 mg S kg^{-1}) > unfertilized control (150.84 mg S kg^{-1}).

Nevertheless, in the case of the subsurface soil (15–30 cm depth) layer, the concentration of total S considerably varied from 119.80 to 193.11 mg S kg^{-1} among different IPNS options over the periods (Tables 2, 3). A significantly higher total S content was recorded with OF observed by the IPNS + C,

TABLE 4 Relationship (r-values) between S-fractions of rice-wheat cropping system.

Properties	WSS	Heat SS	$NaHCO_3$-ES	Total S	Inorganic S	Organic S
Available S	0.905**	0.858*	0.907**	0.892**	0.920**	0.897**
WSS	1	0.965**	0.955**	0.985**	0.985**	0.977**
Heat SS		1	0.898**	0.944**	0.939**	0.932**
$NaHCO_3$-ES			1	0.983**	0.954**	0.988**
Total S				1	0.986**	0.998**
Inorganic S					1	0.983**

**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).
NS, Non-significant.

IPNS + B, IPNS, STCR, NPK, and unfertilized control plots. A plot with OF indicated its significant superiority over the rest of the treatment combinations. The improvement in total soil S may be due to the integrated nutrient supply options (Dutta et al., 2013).

Impact on sulfur fractions contribution

Organic and total sulfur were the dominant fractions of sulfur in both soil layers over the periods (Figures 4, 5). For both soil layers and different treatment combinations, total sulfur contributed the highest 41% in control followed by NPK and STCR 40% each and 38% each in IPNS + B, IPNS + C, and OF (Figure 4). Meanwhile, in the case of 15–30 cm soil layer, the results showed that highest 38% each total sulfur in control, IPNS + C, and OF followed by 37% each total sulfur in NPK, STCR, and IPNS + B, and the lowest total sulfur concentration 36% was reported in IPNS (Figure 5).

Data showed that cumulative results of different sulfur fractions varied in both soil layers among the treatments. Maximum fraction contributions in total S (39%) were followed by the organic S (35%), $NaHCO_3$-ES (7%), heat SS (7%), and 4% each of WSS, available S, and inorganic S in the 0–15 cm soil layer. Nevertheless, in the case of 15–30 cm soil layers, they were reported in the following order: total S > organic S > heat SS > $NaHCO_3$-ES > WSS ≥ inorganic S and available S under different nutrient management practices (Figure 6). IPNS options improve nutrient availabilities (Urkurkar et al., 2010; Subehia et al., 2013).

Relationship between sulfur pools

The relationship between different S pools was significantly influenced by different IPNS options (Table 4). The results showed the positive correlation of available S with WSS ($r = 0.905^{**}$), heat SS ($r = 0.858^{*}$), $NaHCO_3$-ES ($r = 0.907^{**}$), total S ($r = 0.892^{**}$), inorganic S ($r = 0.920^{**}$), and ($r = 0.897^{**}$). In case of WSS, it was significantly correlated with heat SS ($r = 0.965^{**}$), $NaHCO_3$-ES ($r = 0.955^{**}$), total S ($r = 0.985^{**}$), inorganic S ($r = 0.985^{**}$), and organic S ($r = 0.977^{**}$). Similarly, heat SS was also positively correlated with $NaHCO_3$-ES ($r = 0.898^{**}$), total S ($r = 0.944^{**}$), inorganic S ($r = 0.939^{**}$), and organic S ($r = 0.932^{**}$). This remark is in close pact with Borkotoki and Das (2008).

Conclusion

Sulfur mining due to the indiscriminate use of mineral fertilizers and manure has encouraged the occurrence of deficiency. The results of this long-run field experiment revealed that the integrated use of nutrients has significantly increased different sulfur pools under RWCS as compared to the unfertilized control plots. They indicated that different treatment combinations had a significant correlation with different pools of sulfur. Significantly, the highest sulfur fraction contributions as total S (39%) followed by the organic S (35%), $NaHCO_3$-ES (7%), heat SS (7%), 4% each of WSS, available S, and inorganic S (4%), meanwhile total S > organic S > heat SS > $NaHCO_3$-ES > WSS ≥ inorganic S and available S under 0–15 and 15–30 cm soil layer, respectively. We recommend that OF treatment combination contributed the highest in different sulfur pools, followed by IPNS treatment under long-run use of RWCS.

Data availability statement

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

Author contributions

SM: investigation, data curation, writing—original draft, and visualization. BD and SD: conceptualization, investigation, and supervision. MM: software, review, editing, and supervision. VS: conceptualization, investigation, methodology, and supervision. RM: methodology, investigation, data curation, and maintenance. DC: methodology, investigation, review, editing, and supervision. AD: software, formal and data analysis, and editing. VM: data curation, writing, review, visualization, and editing. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Bediger, M. K., Michael, R., Jayaram, N., and Shivraj, B. (1985). Studies on some aspects of soil sulphur and response to sunflower to sulphur application. *J. Ind. Soc. Soil Sci.* 33, 73–77.

Borase, D. N., Murugeasn, S., Nath, C. P., Hazra, K. K., Singh, S. S., Kumar, N., et al. (2020). Long-term impact of grain legumes and nutrient management practices on soil microbial activity and biochemical properties. *Arch. Agron. Soil Sci.* 14, 2015–2032. doi: 10.1016/j.ecolind.2020.106322

Borkotoki, B., and Das, K. N. (2008). Forms of sulphur and their relationship with soil properties in entisols, inceptisols and alfisols of Assam. *J. Indian Soc. Soil Sci.* 56, 186–191.

Chesnin, L., and Yien, C. H. (1950). Turbidimetric determination of sulphur. *Soil Sci. Soc. Am. Pro.* 15, 134–136. doi: 10.2136/sssaj1951.036159950015000C0032x

Dhawan, G., Dheri, G. S., and Gill, A. A. S. (2021). Nitrogen budgeting of rice-wheat cropping system under long-term nutrient management in an inceptisol of north India. *Eur. J. Agron.* 130, 126376. doi: 10.1016/j.eja.2021.126376

Dubey, P. K., Singh, A., Raghubanshi, A., and Abhilash, P. C. (2021). Steering the restoration of degraded agroecosystems during the United Nations decade on ecosystem restoration. *J. Environ. Manag.* 280, 111798. doi: 10.1016/j.jenvman.2020.111798

Dutta, J., Sankhyan, N. K., Sharma, S. P., Sharma, G. D., and Sharma, S. K. (2013). Sulphur fractions in acid soil continuously fertilized with chemical fertilizers and amendments under maize-wheat system. *J. Ind. Soc. Soil Sci.* 61, 195–201.

Eisenstein, M. (2020). Natural solutions for agricultural productivity. *Nature* 588, S58–S59. doi: 10.1038/d41586-020-03445-4

Elferink, M., and Schierhorn, F. (2016). Global demand for food is rising. Can we meet it. *Harv. Bus. Rev.* 7, 2–5. Available online at: https://hbr.org/2016/04/global-demand-for-food-is-rising-can-we-meet-it

Food and Agricultural Organization of the United Nations (FAO) (2009). UNESCO. *Global Agriculture Towards* Available online at: www.fao.org.

Gomez, K. A., and Gomez, A. A. (1984). *Statistical Procedures for Agricultural Research*. New York, NY: John Wiley and Sons, 680.

Jamal, A., Moon, Y., and Abdin, M. Z. (2010). Sulphur-A general overview and interaction with nitrogen. *Aust. J. Crop Sci.* 4, 523–529. Available online at: http://www.cropj.com/jamal_4_7_2010_523_529.pdf

Kilmer, V. J., and Nearpass, D. C. (1960). The determination of available sulphur in soils. *Proc. Soil Sci. Soc. Am.* 24, 337–340. doi: 10.2136/sssaj1960.03615995002400050011x

Kopriva, S., Malagoli, M., and Takahashi, H. (2019). Sulfur nutrition: impacts on plant development, metabolism, and stress responses. *J. Exp. Bot*. 70, 4069–4073. doi: 10.1093/jxb/erz319

Kumar, V., Pandey, A. K., Prasad, R. K., and Prasad, B. (2011). Long-term influence of organic and inorganic sulphur and fertility levels on yields, distribution and build-up of sulphur under rice-wheat cropping system in Calciorthents. *J. Ind. Soc. Soil Sci.* 59, 278–282.

Latare, A. M., Kumar, O., Singh, S. K., and Gupta, A. (2014). Direct and residual effect of sewage sludge on yield, heavy metals content and soil fertility under rice–wheat system. *Ecol. Eng.* 69, 17–24. doi: 10.1016/j.ecoleng.2014.03.066

Meena, S. K., Dwivedi, B. S., Meena, M. C., Datta, S. P., Singh, V. K., Mishra, R. P., et al. (2022). Long-term nutrient supply options: strategies to improve soil phosphorus availability in the rice-wheat system. *Sustainability* 14, 8629. doi: 10.3390/su14148629

Nazar, R., Iqbal, N., Masood, A., Syeed, S., and Khan, N. A. (2011). Understanding the significance of sulphur in improving salinity tolerance in plants. *Environ. Exp. Bot*. 70, 80–87. doi: 10.1016/j.envexpbot.2010.09.011

Rakshit, A., Meena, V. S., Chakraborty, S., Sarkar, B., and Ghosh, S. (2022). Editorial: adaptive farming sustainability practices: fundamentals to advances. *Front. Sustain. Food Syst.* 6, 823437. doi: 10.3389/fsufs.2022.823437

Rongzhong, Y., Wright, A. L., Orem, W. H., and McCray, J. M. (2010). Sulfur distribution and transformations in everglades agricultural area soil as influenced by sulfur amendment. *Soil Sci.* 175, 263–269. doi: 10.1097/SS.0b013e3181e16168

Sahota, T. S. (2012). Importance of sulphur in crop production. *Ont. Farmer Northwest Link* 46, 11–12.

Sandhu, P. S., Walia, S. S., Gill, R. S., and Dheri, G. S. (2020). Thirty-one years study of integrated nutrient management on physico-chemical properties of soil under rice-wheat cropping system. *Commun. Soil Sci. Plant Anal.* 51, 1641–1657. doi: 10.1080/00103624.2020.1791156

Satyanarayana, T., and Tewatia, R. K. (2009). "State wise approaches to crop nutrient balances in India," in *Proceedings of the IPI-OUAT-IPNI International Symposium on Potassium Role and Benefits in Improving Nutrient Management for Food Production, Quality and Reduced Environmental Damages.* Bhubaneswar, 467–485.

Scherer, H. W. (2009). Sulfur in soils. *J. Plant Nutr. Soil Sci.* 172, 326–335. doi: 10.1002/jpln.200900037

Shi, J., Chen, H., Arocenaa, J. M., Whitcombe, T., Thring, R. W., and Memiagh, J. N. (2016). Elemental sulfur amendment decreases bio-available Cr-VI in soils impacted by leather tanneries. *Environ. Pollut.* 212, 57–64 doi: 10.1016/j.envpol.2016.01.045

Singh, A., Dubey, R. K., Bundela, A. K., and Abhilash, P. C. (2020). The trilogy of wild crops, traditional agronomic practices, and UN-sustainable development goals. *Agronomy* 10, 648. doi: 10.3390/agronomy10050648

Singh, A. K., Amgain, L. P., and Sharma, S. K. (2000). Root characteristics, soil physical properties and yield of rice (*Oryza sativa*) as influenced by integrated nutrient management in ricewheat (*Triticum aestivum*) system. *Ind. J. Agron*. 45, 217–222.

Singh, P., and Saini, S. P. (2021). Micronutrients availability in soil-plant system as influenced by long-term integrated nutrient management under rice-wheat cropping. *J. Plant Nutr*. 45, 457–470. doi: 10.1080/01904167.2021.1943680

Soaud, A. A., Al Darwish, F. H., Saleh, M. E., El-Tarabily, K. A., Sofian-Azirun, M., and Rahman, M. M. (2011). Effects of elemental sulfur, phosphorus, micronutrients and Paracoccus versutus on nutrient availability of calcareous soils. *Aust. J. Crop. Sci.* 5, 554–561. Available online at: http://cropj.com/rahman_5_5_2011_554_561.pdf

Subehia, S. K., Sepehya, S., Rana, S. S., Negi, S. C., and Sharma, S. K. (2013). Long-term effect of organic and inorganic fertilizers on rice (*Oryza sativa L.*)-wheat (*Triticum aestivum L.*) yield, and chemical properties of an acidic soil in the western Himalayas. *Expl. Agric*. 49, 382–394. doi: 10.1017/S0014479713000173

Tabatabai, M. A., and Bremner, J. M. (1972). Distribution of total and available sulphur in selected soils and soil profiles. *Agron. J.* 64, 40–44. doi: 10.2134/agronj1972.00021962006400010013x

Tiwari, K. N., and Gupta, B. R. (2006). Sulphur for sustainable high yield agriculture in Uttar Pradesh. *Indian J. Fertil.* 1, 37–52.

Turan, M. A., Taban, S., Katkat, A. V., and Kucukyumuk, Z. (2013). The evaluation of the elemental sulfur and gypsum effect on soil pH, EC, SO4-S and available Mn content. *J. Food Agric. Environ.* 11, 572–575.

Urkurkar, J. S., Tiwari, A., Chitale, S., and Bajpai, R. K. (2010). Influence of long-term use of inorganic and organic manures on soil fertility and sustainable productivity of rice (*Oryza sativa*) and wheat (*Triticum aestivum*) in Inceptisols. *Indian J. Agric. Sci.* 80, 208–212.

Williams, C. H., and Steinbergs A. (1959). Soil sulphur fractions as chemical indices of available sulphur in some Australian soils. *Aust. J. Agric. Res*. 10, 340–352. doi: 10.1071/AR9590340

Woolston, C. (2020). Healthy people, healthy planet. *Nature* 588, S54–S56. doi: 10.1038/d41586-020-03443-6

Zenda, T., Liu, S., Dong, A., and Duan, H. (2021). Revisiting sulphur-the once neglected nutrient: it's roles in plant growth, metabolism, stress tolerance and crop production. *Agriculture* 11, 626. doi: 10.3390/agriculture11070626

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EDITED BY
Caterina Batello Cattaneo,
Food and Agriculture Organization of the United Nations, Italy

REVIEWED BY
Johanna Jacobi,
University of Bern, Switzerland
Jimena Gomez,
Food and Agriculture Organization of the United Nations, Vietnam

*CORRESPONDENCE
Alexandra Rodríguez
arodriguez@conquito.org.ec
David Jácome-Polit
cdjacomepolit@gmail.com

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Agro-ecological urban agriculture and food resilience: The Case of Quito, Ecuador

Alexandra Rodríguez[1]*, David Jácome-Polit[2]*, Alain Santandreu[3], Denisse Paredes[4] and Nataly Pinto Álvaro[5]

[1]Head of the Participatory Urban Agriculture Project (AGRUPAR), The Agency of Economic Promotion (CONQUITO), Quito, Ecuador, [2]Rikolto International, University of the Americas (UDLA), Quito, Ecuador, [3]Consortium for Health, Environment, and Development (ECOSAD), Lima, Peru, [4]Rikolto International, Universidad Tecnológica Equinoccial (UTE), Quito, Ecuador, [5]Rikolto, Quito, Ecuador

The rural and urban divide, promoted by capitalism first and global neoliberalism later, has characterized the countryside as synonymous with "backwardness" and established the city as a model for "progress. " In recent years, promoting agriculture in cities seemed counterintuitive. Nevertheless, during the last decades, agricultural practices in the urban realm have been encouraged, and with great effort, by a group of cities worldwide. Quito is one of them. The Participatory Urban Agriculture Project (AGRUPAR) has promoted and supported urban agriculture in Quito for almost 20 years. However, aware that the food situation of its population requires stronger efforts, the city has decided to go beyond urban agricultural production. Led by AGRUPAR, and together with other municipal actors, such as the Metropolitan Directorate of Resilience, and the Secretariat of Productive Development, the Municipality of the Metropolitan District of Quito (MDMQ) is implementing public food policies that have outlined, as one of their central objectives, the need to strengthen the city's food security and food resilience. This text presents a brief history of urban agriculture in Quito and reviews some of the achievements of AGRUPAR. Based on this experience, the authors hypothesize that cities that have gone from promoting urban orchards to establishing urban agricultural programs are in a better position to implement food policies as a contribution to resilience and sustainable urban development. This article displays the importance of clearly understanding the food value chain and the set of strategic dimensions that currently shape the agri-food system. The aim is to better connect the production, processing and transformation, distribution, sale and storage, commercialization, consumption, and post-consumption with the right to food, the right to the city, and a healthy environment to achieve food security. Although the results achieved thus far are valuable, if the benefits of urban agriculture are to contribute to improving Quito's food security and resilience, additional progress is necessary. Therefore, it is imperative that a proposal be presented which includes urban agriculture as part of a city-scale urban policy.

KEYWORDS

urban farming, climate change adaptation, food policy, food resilience, agroecology

Agriculture and the city

Throughout history, cities have emerged thanks to increased food supply and availability due, among other things, to the introduction of irrigation, increased production, trade, and commerce (Soja, 2001). For Lefebvre (1978) and Maisels (1993) the origin of the city has to do with the agricultural revolution that results in the formation of the first agricultural villages. Along the way, the vision of nature changes from being a wild space from which we must protect ourselves to a basket of resources that we can use to our advantage (Gudynas, 2011; Harvey, 2018). For Mougeot (1999) and Da Silva (2006), urban agriculture is a process as old as cities themselves, and the perceived separation between agri-food production and cities is a recent invention in urban history, where "the Food stopped being a human right to become a business" (Duch, 2011).

For quiteños (inhabitants of Quito) agriculture is not a new practice. The Quitu-Cara culture, one of the first occupants in the territory, created important food infrastructures such as agricultural terraces on the slopes of mountains and ridge systems on the dried-up beds of the lagoons. These infrastructures provided local food supply, which later helped raise intensification of production, to allow for sustenance of the population growth over time. With the arrival of the Incas, criteria for maximizing soil use and sophisticated hydraulic systems were incorporated. This permitted the inhabitants to take advantage of the land considered unsuitable for agricultural production, and helped them to overcome the complications presented by adverse weather. As a result, tools, fertilization processes, soil conservation, and optimization of water use were innovated, while simultaneously managing to domesticate a wide variety of species in diverse climatic conditions and ecological floors. Incan practices included a sowing calendar, public infrastructure (under today's idea of public e.g., streets, parks, water utilities), and a research methodology to improve food production. These practices allowed locals to connect with the higher world. It is estimated that they cultivated and domesticated about seventy plant species.

Ancestral knowledge and alternative technologies are still present when working the "chacra" (small orchards) and applied to the small, cultivated fields managed under the Andean worldview. These are still considered important agroecological bases. Andean production techniques have proven their worth in both technical and scientific support, and in their constant contributions over time. However, with the Spanish colonization this all changed. New crops such as fruit trees, vegetables, cereals, and farm animals were introduced, surpluses were privatized, and the massification of other forms of production replaced traditional forms. People "forgot" tradition. These changes strongly impacted agricultural production systems and, consequently, the population's capacity to access food. Although food security with sovereignty of the entire colonial population was not always achieved, the engravings showing how agriculture was part of the walled cities guarantee to food, are well-known.

Centuries later, agricultural production left the cities and remained in the countryside eliminating the urban use of land for agriculture. Capitalism first and global neoliberalism later, assimilated the rural to "backwardness" and the urban to "progress." With the Green Revolution, agricultural food production became the heritage of large agricultural companies with global practices based on monocultures and the use of chemical synthetic fertilizers. As a result, family agriculture was relegated from public policies (Holt-Gimenez et al., 2006; Altieri and Toledo, 2011), thus misleading the collective memory and original meaning of the people, its culture, and its environment (Maela, 2011). This adverse environment caused urban agriculture to be left out of agricultural public policies and urban development plans, and in turn, develop into an alternative that is practiced in low-income sectors and in the peripherals of the city.

Over time, urban agriculture has developed in Quito, based on the combination of traditional and ancestral practices inherited from the pre-Columbian era (mainly potatoes, corn, broad beans, zambo, pumpkins, beans) with the implementation of microtechnologies typical of urban production (Long, 1996). However, urban agriculture was not able to escape the influence of the Green Revolution (especially the suburban and rural neighborhoods) that triggered the indiscriminate use of agrochemicals, the loss of biodiversity, the irrational use of global common goods (soil, water, air), in addition to breaking with the ties and logic of community work and with the sense of belonging and connection to the land (Santandreu and Rea, 2018). The notion that water, soil, and air, are now referred to as "resources" instead of the idea of being "global common goods" exemplifies this moment in the history of modern agriculture.

Although activities related to agriculture and food production have been carried out since ancient times in Quito, the process of conceptualizing urban agriculture and healthy eating as part of public policy is recent. Furthermore, urban and peri-urban agriculture is seen as an alternative to the loss of productive areas due the accelerated urban growth propelled by the real estate market.

AGRUPAR, a participatory urban agriculture project

Despite finding multiple approaches and definitions, in this article, urban agriculture is defined as a renewed way of understanding the relationships between the countryside and the city, as well as those established by people with each other, and the correlation between nature and the city. Seeing as urban agriculture is not synonymous to rural agriculture on a smaller scale, it is necessary to analyze some of its characteristics in further detail. It should be kept in mind that although implementing urban orchards is necessary, it is not a sufficient condition to further urban agriculture as a policy for food and urban resilience.

A variety of activities need to be developed for urban and periurban agriculture to exist. These activities include: (i) the production and/or transformation of fresh produce and/or livestock into products based on agroecological principles, (ii) the promotion of short supply chains to improve food access in the "last mile" and to reduce the environmental burden of transport and storage, (iii) the stimulation of self-consumption and/or market exchange (barter or commercialization) based on social economic principles, (iv) the promotion of healthy foods and avoid offering ultra-processed foods, and (v) the sustainable management of residues that minimizes food loss and waste and favors circular economies, (vi) knowledge exchange as a two-way communication process where urban farmers receive training but also provide feedback to improve and scale better practices

Through the use of appropriate technologies and participatory processes, urban agriculture allows for a sustainable (re) emergence of global common and local goods that take into account local knowledge and culture. Such an approach enables social creativity and fosters the reconnection between people and nature. As a result, a forgotten philosophy of life is recovered (Santandreu and Rea, 2016; Rodríguez, 2018). This concept recognizes a cross-sectoral, transdisciplinary, and multi-stakeholder approach that considers the systemic complexity and multi-dimensionality of urban agriculture. Such approach allows for this activity to become permanent in cities and re-establishes urban agriculture as one of the cornerstones of health and food resilience.

In 2000, with the support of the Urban Management Program for Latin America and the Caribbean (PGU-ALC), the Municipality of the Metropolitan District of Quito (MDMQ) began to implement urban orchards in the northern, central, and southern parts of the city. Soon after, in 2002, The Participatory Urban Agriculture Project (AGRUPAR) was created to address urban and peri-urban production of agricultural products in the Metropolitan District of Quito. Since 2016, with the support of different organizations such as The RUAF Foundation and RIKOLTO, and with the leadership of the Secretariat of Productive Development, to which the Metropolitan Directorate of Resilience was later added, the MDMQ began promoting a public agri-food policy that had urban agriculture as one of its pillars.

AGRUPAR connects the food value chain with a set of strategic dimensions of the agri-food system Rodríguez and Proaño (2016). It promotes the social and solidarity economy that seeks to guarantee food security and sovereignty by incentivizing and enabling the practice especially by the most needed, supports responsible consumption focused on promoting healthy food environments, and seeks to manage losses and waste by exploring the notion of a circular economy. AGRUPAR's approach local agro-ecological food production with the human right to food; the city with a healthy environment; and the governance of the agri-food system to make better decisions to strengthen the city's food resilience (Carasso and Carasso, 2019).

From the beginning, AGRUPAR has transcended the urban border. According to the last census carried on by AGRUPAR in 2020, the project accounted for about 60 hectares of production distributed in spaces of up to 7,500 square meters, throughout its territory. This bridges the divide between sustainable production and healthy consumption, reaffirming a new way of understanding the urban-rural link. The project is estimated to have an annual output of more than 1,200 tons of healthy food. Around 53% of production is destined for self-consumption and 47% is commercialized through different channels.

This practice not only improves access to safe food, but it also promotes healthier family economies by decreasing food spending, increasing income, and becoming a means for living in low-income sectors. It provides an average income of $175 per month, per urban orchard (can belong to a family, an individual, or to the community). The implementation of urban orchards has implied a modification in the family and collective space, symbolically and in practice. This has transformed the dynamics of food environments.

Since 2000, five municipal administrations with different political perspectives and priorities have passed, but AGRUPAR has maintained its core values and principles. Furthermore, over the years, AGRUPAR has strengthened its relations with various Ecuadorian actors (different levels of government, civil society, the private sector, academia and with citizens) and has deployed international alliances with diverse cooperation agencies, researchers, and other governments, that have allowed access to resources and new ways of addressing problems.

The Programme has also contributed to strengthening social relations between producers and consumers, as well as the inclusion of small farmers and vulnerable groups in Quito's food system in Quito Chiara Tornaghi (2018). It has created subsystems for vegetables, fruits, and medicinal plant production. The programme also provides seedlings, seeds, organic inputs (e.g., fertilizers and mulch) and bio inputs (e.g., organic pesticides), complementing the urban farm with the technical raising of minor species, beekeeping and artisanal food processing for value addition. Innovations have also been made to improve productive tools and infrastructure such as micro greenhouses and drip irrigation systems. Furthermore, AGRUPAR has supported the production of certain types of seeds to create a seedbank, however, seed production is limited to the varieties that are supported by the climatic floor, hence making AGRUPAR dependent at a certain extent of imported seeds.

For example, the design of rainwater harvesting systems, low-cost drip irrigation with easy implementation, and mulch, among others, are direct effects of optimal water consumption in urban agriculture. By using a 3 mm sheet per square meter, irrigation systems optimize 95% of water used for production. This simple technology has been adopted by urban farmers to improve resource efficiency and the quality of the produce. Since the water used to irrigate is potable, these savings become even more important. Spreading the knowledge of these innovations among the population allows for urban agriculture in the city to continue to progress.

As a general rule producer's lack of access to appropriate capacities are often one of the main barriers for sustainable urban agriculture to gain scale. AGRUPAR has provided constant capacity-building support to the target populations, by disseminating sustainable urban agriculture practices and innovations throughout several trainings and knowledge building activities. In 2019, AGRUPAR supported training and technical monitoring for the cultivation and handling of small animals and food processing in more than 1,800 urban orchards (see Table 2). Currently, the program supports more than 2,200 urban orchards and aims at increasing this number by 200 urban orchards per year.

Food processing is given as an option to save food (when products do not meet the size, shape, color, or appearance for fresh marketing) and to offer longer conservation of products, while adding value through processing, thus becoming an interesting line of business in local bio-fairs. The Census of the AGRUPAR project, also was determined that food processing represents 15% of the entrepreneurial options of farmers. Farmers process 82 types of products of the total volume sold at fairs. Processed products represent 14.87% in relation to weight (kilos) and 29.24% in relation to sales generated in dollars.

AGRUPAR has 15 bio-fairs (with 19 weekly frequencies, an average of 850 bio-fairs take place per year) for the direct sale of surplus production, where more than 105 types of products are offered while also reducing the distance that products need to travel and creating shorter circuits (see Figure 1).

However, the scale in which urban agriculture shows the greatest contributions to the city, is at the neighborhood level. This article defines neighborhood as a subdivision of the urban territory that presents its own identity, which is historical, cultural, and urban, and gives a sense of belonging to its inhabitants, without having a specifically defined territory or population. Yet, in a neighborhood, various food neighborhoods can coexist, nucleated around, or connected to public food markets, or through the relationships established by their inhabitants, regardless of political or administrative differences. Today, urban orchards are considered an important component of food neighborhoods as it provides access to affordable and fresh and nutritious food locally produced.

AGRUPAR also distinguishes the scales of intervention. An activity such as urban agriculture typically has positive consequences at the food-neighborhood level by providing food to its population. However, it must be noted that on a larger scale, for example on a parish or metropolitan level, that is insufficient.

Currently, one of the challenges of urban agriculture, based on the type of agroecological approach that is implemented in Quito, such as developing creative solutions with a holistic, nature-based approach to agriculture. There is evidence of additional benefits such as erosion control practices which are used to recover degraded urban soil that does are not typically used for agriculture. This could achieved by conserving the fertility and soil biota (considering the soil as a living being that can be restored, maintained, and improved), using urban organic waste for compost and humus production, or utilizing the soil as a base for "hotbeds." Additionally, minor animal farming in permitted areas of the city allows a regular supply of compost for the maintenance of soil fertility.

For food production in spaces that do not have soil available, such as balconies, patios, and terraces, it is essential to guarantee the supply of organic inputs with an agroecological base. These spaces have led individuals and communities to find practical and simple solutions, such as using boxes, bottles, tires, vertical PVC tube modules, among other alternatives. However, these solutions require external contributions of organic fertilizer. Combating weeds, pests, and diseases in crops, without putting public health at risk, requires the use of alternative means such as bio inputs and controlling invasive species by natural means.

These organic inputs are preferably made in the production unit itself, exchanged between farmers, or acquired externally. If acquired externally, these products must be compatible with organic regulations or certified. All in all, agro-ecological production has created alternatives that resemble the normal function of nature and thereby, enables circular economies.

For production practices, the use of seeds, seedlings, and dissemination training materials (please refer to Table 1) must respond to specific geographic conditions, seeking the rescue, preservation, and multiplication of own/native varieties, in addition to considering others that may initially be from an external provider, but necessary to increase agrobiodiversity from the urban farm and contribute to a diversified diet. Under no circumstances does AGRUPAR accept the use of genetically modified organisms (Rodríguez, 2018).

AGRUPAR represents an important source of income and savings for urban farmers. It is also an urban sustainability strategy that contributes to improving peoples' living conditions, enables nutrient recycling, develops water management, and promotes biodiversity. AGRUPAR also has a positive impact in the reduction of deserts and food swamps, increasing the availability of food in situations of chronic stress or of severe disruptions of the agri-food system due to environmental, political, or socioeconomic events.

Since 2002, AGRUPAR has been promoting the self-production of food by taking advantage of vacant, unproductive, or underutilized spaces in the city as a strategy to effectively increase food security with sovereignty and improve food and urban resilience. At a neighborhood scale, AGRUPAR improves the availability, access, and quality of food consumed

TABLE 1 AGRUPAR training topics.

Training provided by AGRUPAR	
Topic	**Content**
Urban Agriculture	Food safety, installation of the urban orchard, production of organic fertilizers, planting, crop management, pest and disease control, harvest, post-harvest, planting, and the phases of the moon.
Productive Infrastructure	Construction of greenhouses and installation of drip irrigation systems.
Poultry Farming (quail, chicken, and posture birds)	Facilities, feeding, and reproductive and sanitary management.
Beekeeping	Installation of the apiary and management of hives.
Guinea Pig Breeding (animal protein for the Andean region)	Facilities, feeding, and reproductive and sanitary management.
Therapeutic Use of Food	Medicinal use of food grown in orchards.
Healthy Food Habits	Promotion of adequate nutrition to avoid chronic non-communicable diseases.
Food Processing	Add value through the processing of production surpluses: snacks, baked goods, meat, food preservatives, and dehydrated food.
Production Costs	Elaborate costs of crops that are implemented in the orchard to define sale prices and profits.
Quality Certifications	Compliance with local regulations.
Seed and seedling system	
AGRUPAR's Role	Acquires the necessary material for the beneficiaries in quantities that fulfill a didactic purpose for learning and allows for the first plantings.
Beneficiaries' Role	Acquire and/or generate their own seeds for Andean crops (12 h of light and 12 h of darkness, and not having four seasons). The main objective is to have local varieties from the Andes, such as potato, oca, mashua, melloco, quinoa, amaranto and complemented with products from other origin centers, such as fruits and vegetables and medicinal plants. AGRUPAR does not allow for GMO as it has an agroecological base. Women farmers have been trained to form micro-enterprises with certified production of seedlings, subsequently acquired by AGRUPAR, to be used by other farmers safely.

Source: AGRUPAR.

by neighbors, while respecting the diversity of options typical of a multicultural society. Quito's urban orchards have a production capacity of 1.35 million kilograms of healthy food each year, of which 57% (769,000 kilograms) is consumed by producers and their families and 43% (581,000 kilograms) is sold *via* various short supply chains. Each week, about 11 tons of fresh and healthy food are destined for the city's most vulnerable neighborhoods.

Under a gender lens, according to a study (unpublished), "Growing More Than Food: Urban Agriculture & Empowerment, A Summary of Findings," by Kate Oviatt from the University of Colorado, 2016, in terms of empowerment, the results of urban agriculture are positive. Regarding the economic independency of women, 88% of women expressed they have control over their own money and 11% noted they share control with their husbands. In reference to food literacy, it was determined that 89% of urban farmers have learned about healthy eating and 99% believe that urban orchards have improved their family's nutrition. In fact, 91% of urban farmers found that they were eating more fruits and vegetables. Additionally, 93% of these farmers noticed that they are more active during the day and 98% say that the quality of the food their family consumes has improved. In conclusion, 83% of urban farmers say that their overall health has improved.

Furthermore, researchers in Ecuador found a direct association between women's empowerment in agroecology and their diet. Women involved in agroecology are able to build social and human capital through their engagement in local markets and barter. These women also recognize that diversity in the farm is reflected in the diversity on their plate (Deaconu et al., 2019). Related to this, a study developed in the Peruvian highlands demonstrates a clear association between farm biodiversity and dietary improvement among women (Jones et al., 2018).

Urban agriculture, urban resilience, and food resilience

The generation and adaptation of food production systems to the urban ecosystem face fundamental challenges that go beyond urban farming and must be faced with broader sustainable food policies. To achieve the success of agricultural production in the urban area it is necessary to reflect on

TABLE 2 Processed products in Quito.

Type of processed products	%
Meat	26.47
Preserved Food	21.76
Snacks	20.00
Baked Goods	17.06
Dairy	14.71

Source: AGRUPAR's census 2020.

possible shocks and the effects of climate change. Accompanying measures must be applied to maintain stable and diversified food systems to improve the resilience of urban orchards, and in a larger extent, contribute to the food resilience of neighborhoods, first, and of the city, later. As of today, in the context of urban and socio-economic development in Quito, achieving food security with sovereignty means strengthening the city's capacity to face severe disruptive events of environmental, social, economic and political nature. Quito is no stranger to these types of disruptions that severely impact the nutrition and well being of the population.

In October 2019, indigenous organizations, and a large part of the population, protested in response to harsh economic measures established by the Executive Power. Such measures included the elimination of the fuel subsidy and cuts to public spending. Tens of thousands of people mobilized, blocking the access roads and the main roads of the city. After 14 days of blockades, the shortage of fresh food was notorious, especially in the low-income neighborhoods in the south and north-west of the city. This is not the only example of a social mobilization blocking Quito's streets and causing severe food shortages. Similar situations took place in 1997, with protests that culminated in the resignation of President Abdalá Bucaram. In 2000, President Jamil Mahuad resigned after an economic crisis that resulted in the dollarization of the country. In 2005, President Lucio Gutiérrez was also removed after deep social unrest. Today, the COVID-19 pandemic, once again, has tested the capacity of urban agriculture to contribute to food security with sovereignty, especially in the low-income sectors. These events have left us with important lessons.

Based on the urban resilience concept proposed by Meerow et al. (2016), we know that food resilience is a property of complex systems which exist when the socio-ecological and socio- technical networks that constitute the city (at different temporal and spatial scales) manage to maintain or can quickly return to previous functions, guaranteeing availability and access to sufficient and nutritious food for all people permanently.

Thus, it is the ability of a system to adapt to a changing context that can affect its operation. However, Quito's agrifood system is particularly vulnerable since only 5% of the goods consumed in the city are produced within the city's limits. This production is continuously threatened by the real estate and housing market. As a result today the concentration of supply goods occur in two opposite points of entry in the city that, in turn, connect with large areas of the country that are highly exposed to natural hazards. In this scenario, during the response to face political disruptions or the sanitary emergency, Quito's urban orchards were able to reconfigure some of its food outlets to offer solutions to the food provision problems at various scales and without losing the ability to provide healthy, uninterrupted, and diverse food for producing families. AGRUPAR assisted in the scarcity of food with surplus produce.

Surplus produce was sold *via* four channels:

a) Occasional sales as crops are ready for harvest (a few bundles of radishes, a few kilos of tomatoes or potatoes, a couple of heads of broccoli, cabbage, lettuce, and chicken, among others).
b) Weekly sale of baskets of 10–15 seasonal varieties (possibly including chicken, pork, or eggs) to families in the neighborhood or in nearby towns; transactions which take place in the garden.
c) Sale of a fixed quantity and selection of produce *via* collaborative supply chains. Transactions are made through a third party, who establishes contact with consumers, assembles baskets by collating surplus produce from various producers, and delivers them to homes.
d) Barter.

One of the best ways to increase the resilience of a population is to reduce the socio-economic vulnerability in the city in a sustained way to avoid increasing food risk, especially among the poorest. This is possible as shown above. However, it is important to remember that urban agriculture must be considered a constituent part of a much broader agri-food system. Its role and scope are essential and contribute to forming strategies that help to address challenges at different scales, and this should be incorporated into urban planning instruments and policies. Doing this, amplifies the city's response capacity and scale to a socio-economic vulnerability.

It is imperative to understand the role of the different actors in the system. In 2017, the Agri-Food Pact of Quito (PAQ) was created, where different representatives expressed their commitment to developing a sustainable and resilient agri-food system to guarantee the provision of healthy food for the entire population, especially for the most vulnerable (Santandreu et al., 2019). This organization created multiple synergies and thus, an opportunity to advance in the governance agenda in favor of further public policy planning and response capacity to face disruptive events.

Based on the Trajectories of Change approach (Santandreu and Betancourt, 2019), which starts by recognizing previous actions implemented by communities to identify problems and solutions, the Food Action Plan, as part of the Agri-Food Strategy of Quito, proposes key policies that cover at different scales the entire value chain and strategic dimensions of the agri-food system.

A conceptual framework, known as food hubs, aims at uniting the human right to food, the right to the city, and the sovereign approach to food security, as components of a sustainable food environment without degrading it (Cohen-Shacham et al., 2016). This framework is a result of a previous study carried out in Quito and differs from other studies of food hubs by going beyond a simple analysis of food distribution in cities (Argüello et al., 2017). This plan relates different components of the food value chain in a systemic understanding to plan for the improvement in the operation of the whole system (Jácome-Pólit et al., 2019a). The study identified food hubs as one of the food public policy actions most likely to strengthen food resilience by connecting, at the food neighborhood scale with a great diversity of actors in the agri-food system.

Examples of these include urban orchards, markets, bio-fairs food distributors (formal and informal), stores, supermarkets, hotels, restaurants, food programs, public food infrastructure, and consumers. Under this approach, urban agriculture has the potential to promote strong relationships between people and institutions on a local scale therefore improving the social fabric and the capacity for a collective response to a disruptive event. Although their contribution in the quantity of food is not significant at a city scale, their contribution to the connection between people in different components of the food system is extremely significant and increasingly necessary (Jácome-Pólit et al., 2019).

Later, understanding the environmental and social impacts that occur at each stage of this interconnected system is possible by identifying the links between production (urban agriculture and rural food production), transport and storage (logistics and urban mobility), marketing (in markets, fairs, stores, warehouses, supermarkets, hotels, and restaurants), consumption (by people, social organizations, and institutions such as schools), social programs (provide food), food reuse, and waste management programs.

To a greater extent, the Quito Agrifood System Resilience Strategy (a work in progress) proposes food hubs as centralities connected at a metropolitan scale (see Figure 2). As a mechanism, neighborhoods, urban and peri-urban areas, and rural agricultural landscapes, should be considered by the institutions that formulate public policies at different governmental levels to manage the whole system. In this context, food hubs are planned territorially and function as a distributed network that permanently offers accessible sociocultural-relevant foods, especially where they are most needed (see Jácome-Pólit et al., 2019b). A food hub has a level of autonomy, but at the same time, it can jointly work with other food hubs, creating an increasingly self-sufficient system. This is, arguably, the most important aspect that builds resilience into the city's food system.

This is where urban food production with an agro ecological base takes a different dimension. For this reason, the inclusion of food hubs as urban planning tools, that includes urban farming, is necessary. People are encouraged to produce healthy food locally, thereby responding to the need to expand the program which includes the development of urban agriculture, use of land, and work. These benefits are extended to other areas of urban management, and help create suitable and healthy food environments by taking advantage of the 13 sq. per capita of green areas available in the city that could offer local and fresh produce for more people.

Furthermore, in a recent study, Paredes (2019) analyses urban agriculture as a mechanism of climate change adaptation, but its effectiveness depends on the scale it intends to support (Adger et al., 2005) and recognizes its positive contribution at a neighborhood scale (Dubbeling and de Zeeuw, 2011). The contribution of this practice lies mainly on reducing vulnerability in social and economic dimensions (FAO, 2014) and, therefore, also reducing the risk posed by climate threats amplified by climate change. However, this capacity is closely related to the system's ability to adapt which in turn is determined by links and feedback loops with other parts of the system.

In the case of AGRUPAR, the reduction of vulnerability as a result of urban agriculture is highly evident at the household and food neighborhood levels. This results partly from strengthening capacities and implementing individual and community urban orchards with direct and continuous technical support for farmers, many representing a highly vulnerable population (Dubbeling and Rodríguez, 2016). The economic independence of female farmers, their improved eating habits, and the empowerment of women are among the documented benefits that show a reduction in vulnerability (Papuccio de Vidal, 2011). Additional factors are the inclusion of other vulnerable actors in decision-making, the developing and strengthening of social networks, personal satisfaction and trust, among others (Oviatt, 2016). Yet, on a metropolitan level, contribution to climate change adaptation and the strengthening of municipal food resilience is lesser.

As a response, urban agriculture has been included in the Climate Action Plan 2015-2025 (and its update to 2050), the Resilience Strategy, and the Agri-Food Strategy of Quito. These strategies, together with the Milan Urban Food Policy Pact signed by the Mayor of Quito in 2016, are all important steps toward a greater understanding of food as a systemic and complex phenomenon that has urban agriculture as one of its touchstones. In 2021 the Land Use and Development Plan, an instrument that guides and organizes the Municipality of Quito's actions allows for budget allocation, placed food security as the foundation of an inclusive and ecological development of the

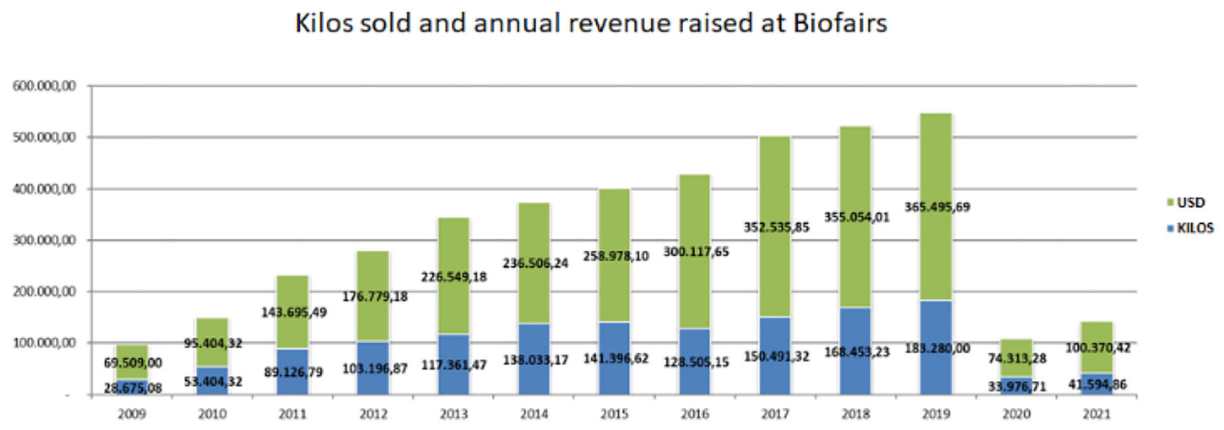

FIGURE 1
Income per Bio-fair per year. Source: AGRUPAR's census 2020.

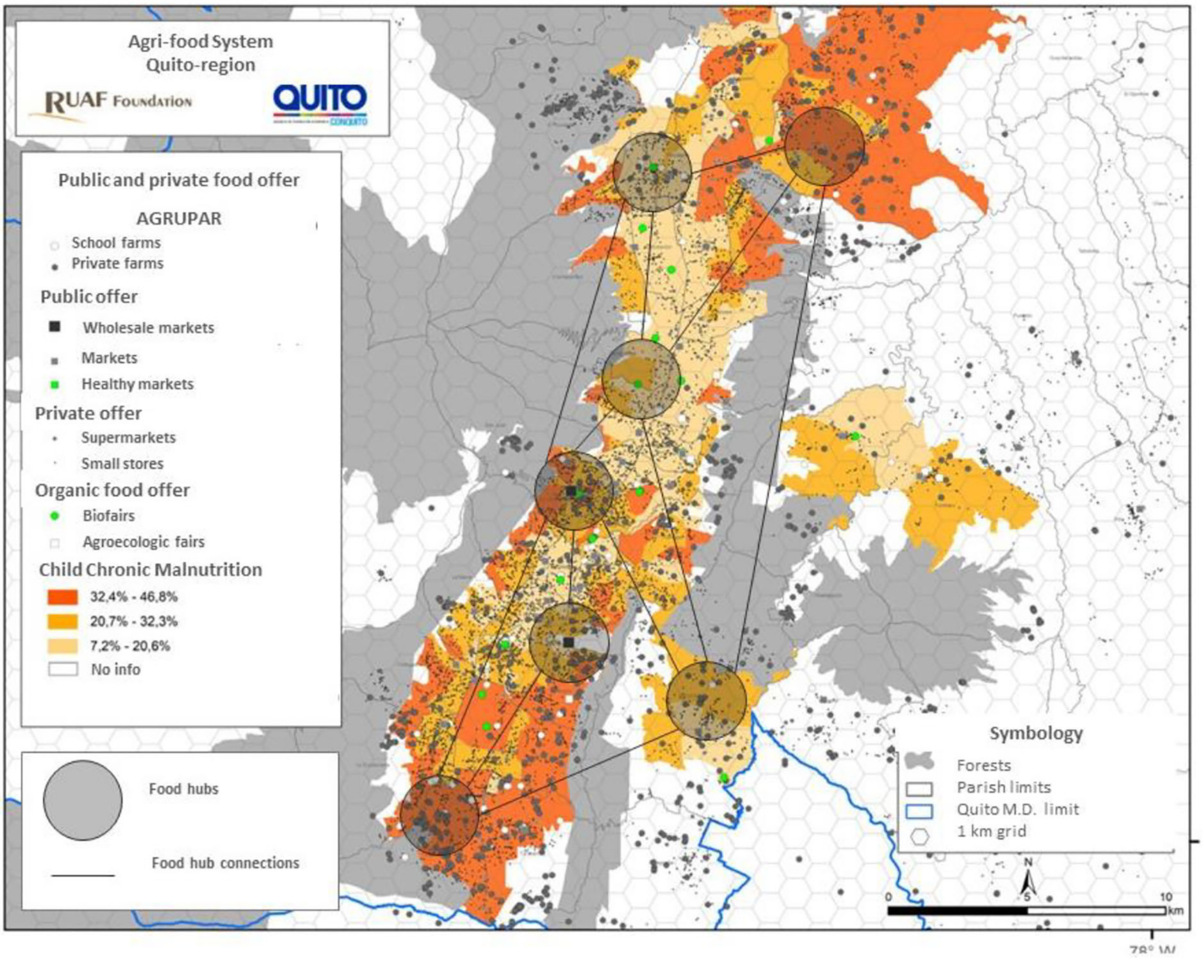

FIGURE 2
Map showing a representation on how food hubs can be understood. Source: Quito's metropolitan information system, AGRUPAR, Ministry of Health Ecuador.

city, and strategic guidelines to scale AGRUPAR's operation have been included. Nevertheless, this is still not sufficient.

Positive contributions on neighborhood and community scales are largely defined by the availability of resources for logistics, which in turn, provide localized assistance to farmers. However, these regulation need to extend to the peri-urban and rural realms, especially when roughly 12% of the area in the Metropolitan District of Quito is considered urban. Until now, these demands for regulations and actions at planning levels go beyond the scope of the program. So far, urban and peri-urban agriculture programs and projects to scale and amplify the capacities of the local government to this end and have yet to be designed and implemented.

Furthermore, AGRUPAR's success shows that it has managed to meet the particular needs of urban farmers and families. This program also benefits from conditions such as the existing agricultural vocation of the population. Traditional and local knowledge that benefits the practice, and the social dynamics of associativism are prevalent in the communities enabling families to adopt AGRUPAR's plans and systems. Yet, the low occurrence of the project as a measure for adaptation to climate change and the city's food resilience shows a deficient capacity to formulate policies and programs that allow amplifying its benefits. This speaks to the complexity of the administrative system of the city and the country.

Relevant actors in the city planning processes have identified a lack of vision, political will, knowledge, and techniques when it comes to incorporating climate change measures in urban development policies. Similarly, in Quito there is evidence of risk management practices that are focused mainly on the response to face disruptive events, leaving prevention and mitigation aside, not to say that the food agenda is usually overlooked. Overcoming these barriers presents an opportunity to strengthen urban agriculture as a measure for climate change adaptation transcending the neighborhood scale. This will also help projects to advance beyond the socio-economic agenda and contribute to the environmental agenda as a possible climate change mitigation and adaptation strategy.

It has been recognized that sustainable and healthy food access impact in different ways all the sustainable development goals[1] and that efforts improving nutrition extend beyond SDG2 and contributes to other SDGs, such as SDG3 improving health and SDG1 working to end poverty[2], which in turn can contribute to close socioeconomic and spatial gaps in cities. This can have important consequences when managing risks in cities like Quito and others by improving the capacity to access and/or replace dwellings (see Hallegatte et al., 2017). In this light, multidisciplinary collaboration is required to contribute simultaneously to different agendas, such as climate change adaption and mitigation, drastically reducing biodiversity loss and tackling malnutrition in all of its forms.

Evidence indicates that important synergies can be created by designing interventions that support the nexus between biodiversity, sustainable production practices, reduced levels of malnutrition and enhancing the resilience of the communities. This systemic approach puts food at the center as the strongest lever to optimize human health and environmental sustainability while ensuring social equity, especially for the most vulnerable (FAO, 2021).

Conclusions

Urban agriculture allows us to envision a renewed relationship between cities and agri-food production while strengthening food security with sovereignty and resilience. This is the objective of The Urban Agriculture Program in Quito (AGRUPAR). The programme has managed to leverage the city's long-standing history with agriculture, its remaining practices to promote and support urban agriculture, and more recently, the construction of an agri-food public policy. For more than 20 years, AGRUPAR has promoted social cohesion, healthy nutrition, the adoption of agroecological principles, and a social and solidarity-based economy, all of which demonstrate important results reducing vulnerability at a neighborhood scale. Nevertheless, considering that Quito is prone to disruptive events, which will be exacerbated in climate change scenarios, AGRUPAR seeks to expand the impact of its practices to a metropolitan scale, triggering food resilience-building processes. These have positive consequences in different manners, among them: by becoming a valid alternative to a process of rapid urbanization that hinders the capacity of the city to produce food within its limits; by strengthening the capacity of quiteñas and quiteños to produce local, agroecological, diverse and nutritious food; and by conserving the fertility and soil biota while creating circular economy processes, among others.

Achieving food security with sovereignty requires important efforts on various points of the food chain such as, addressing underlying and multidimensional structural problems that make current food systems operate erroneously and contribute to the creation of vulnerability in the population. Multiscale analyses of the agri-food system demonstrate that urban agriculture is an important component that strengthens the social fabric and bring institutions and people closer. However, it must be part of broader actions and must accompany

1 A new way of viewing the Sustainable Development Goals and how they are all linked to food, available online at: https://www.stockholmresilience.org/research/research-news/2016-06-14-the-sdgs-wedding-cake.html.

2 NUTRITION AND THE INTERLINKS WITH ALL GLOBAL GOALS, available online at: https://www.powerofnutrition.org/nutrition-and-the-sustainable-development-goals/.

other strategies. In this context, the concept of food hubs is presented as a viable option to strengthen food resilience by connecting various actors of the agri-food system, forming collaboration between actors, and organizing systems. Quito's Agrifood System Resilience Strategy proposes that food hubs be planned and connected territorially and have the capacity to be self-sufficient on a higher degree, yet also work jointly with other food distribution centers building resilience into the city's food system. Together with this, and understanding that the urban periphery and rural area of the Metropolitan District of Quito is large and has a major agricultural production component, the program seeks to scale up urban agriculture and the proposed food hubs serve to take advantage of urban agriculture in a wider territorial scale, for example by promoting productive reconversion of land in peri-urban areas (such as green belts); the creation and management of legal figures for the protection and promotion of agricultural soils (such as urban and peri-urban "soils"), the promotion of agricultural educational parks and the further integration of urban agriculture into the city landscapes. The development of land management policies and secure access to land are fundamental for the sustainability of the local food system and have been included in the Development Plan of the city, yet they remain to be implemented.

Although the amount of food produced under the program may seem insufficient on a metropolitan scale, the adoption of urban agriculture as a means to reconnect people, nature, and cities, is key. Urban agriculture is pivotal in the development of a metropolitan resilient agri-food system and the establishment of food hubs in the city. The success and continuity of AGRUPAR has allowed it to build a strong network across the food chain and lead important public policy processes such as the construction of the Agri-Food Strategy of Quito and the inclusion of urban agriculture in the city's Climate Action Plan, compounding important steps toward the much-needed transformation of the system and the city's future.

Author contributions

DJ-P and AS developed theoretical formalism. AR and DP contributed extensively with field research and analysis. AR, DP, DJ-P, and AS authors contributed to the final version of the manuscript. All authors discussed the results and contributed to the final manuscript.

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References

Adger, W. N., Arnella, N., and Tompkinsa, E. L. (2005). Successful adaptation to climate change across scales. *Glob. Environ. Change* 15, 77–86. doi: 10.1016/j.gloenvcha.2004.12.005

Altieri, M. A., and Toledo, V. M. (2011). The agroecological revolution in Latin America: rescuing nature, ensuring food sovereignty and empowering peasants. *J. Peas. Stud.* 38, 587–612. doi: 10.1080/03066150.-2011.582947

Argüello, L. P., Morganti, E., and Feliú, J. G. (2017). Food hub: una alternativa para alimentar las ciudades de manera sostenible. *Transporte y Territorio* 17, 10–33. Available online at: http://www.redalyc.org/articulo.oa?id=333053\penalty-\@M372002

Carasso, D., and Carasso, N. (2019). "*RUAF* foundation," in *IWMI – CGIAR Water Land and Ecosystems Program. Dinámica y Planificación del Sistema Alimentario en la Ciudad Región Quito*.

Chiara Tornaghi, Ch. (2018). *RUAF Foundation Editorial Urban Agriculture Magazine, 33*.

Cohen-Shacham, E., Walters, G., Janzen, C., and Maginnis, S. (2016). *Nature-Based Solutions to Address Global Societal Challenges*. Gland: IUCN. p. 97.

Da Silva, L. O. (2006). Agricultura: utopías e prácticas urbanas. *Revista Integração* XII(46), 217–230. Available online at: http://www.usjt.br/prppg/revista/numeros.php

Deaconu, A., Mercille, G., and Batal, M. (2019). The Agroecological farmer's pathways from agriculture to nutrition: a practice-based case from Ecuador's highlands. *Ecol. Food Nutr.* 58, 142–165. doi: 10.1080/03670244.2019.1570179

Dubbeling, M., and de Zeeuw, H. (2011). "Urban agriculture and climate change adaptation: Ensuring food security through adaptation," in *Resiliente Cities, Proceedings of the Global Forum 2010*. Springer. doi: 10.1007/978-94-007-0785-6_44

Dubbeling, M., and Rodríguez, A. (2016). A metropolitan agriculture programme for the promotion of integrated territorial planning. *City Reg. Food Syst. Food Waste Manage.* 58–71. Available online at: https://www.fao.org/3/i6233e/i6233e.pdf

Duch, G. (2011). "El bunker" in *Biodiversidad en América Latina*. Available online at: http://www.biodiversidadla.org/Principal/Contenido/Documentos, visitado en diciembre 2011.

FAO (2014). *Ciudades Más Verdes en América Latina y el Caribe: Un Informe de la FAO Sobre la Agricultura Urbana y Preiurbana en la Región*. Reporte, FAO.

FAO. (2021). *Climate Change, Biodiversity and Nutrition Nexus—Evidence and Emerging Policy and Programming Opportunities*. Rome.

Gudynas, E. (2011). "Desarrollo y sustentabilidad ambiental: diversidad de posturas, tensiones persistentes," in *la Tierra no es Muda:Diálogos Entre el Desarrollo Sostenible y el Postdesarrollo,* eds A. matarán-Ruiz, and F. López-castellano, (Granada: Universidad de Granada), 69–96.

Hallegatte, S., Vogt-Schilb, A., Bangalore, M., and Rozenberg., J. (2017). *Unbreakable: Building the Resilience of the Poor in the Face of Natural Disasters*. Climate Change and Development Series. Washington, DC: World Bank. doi: 10.1596/978-1-4648-1003-9

Harvey, D. (2018). *Justicia, Naturaleza y la Geografía de la Diferencia, Primera*. Quito: IAEN-Instituto de Altos Estudios Nacionales del Ecuador y Traficantes de sueños. Available online at: https://www.traficantes.net/sites/default/files/pdfs/PC18_Harvey_web.pdf

Holt-Gimenez, E., Altieri, M. A., and Rosset, P. (2006). *Diez Razones Contra la Nueva "Revolución Verde" de Rockefeller y Gates, Viento Sur*. Available online at: https://vientosur.info/spip.php?article360 (accessed 15 Diciembre, 2019).

Jácome-Pólit, D., Cubillo, P., Paredes, D., and Ruiz Villalba, P. (2019b). "RISQ: Risk Assessment Tool for Quito," in *Advanced Studies in Energy Efficiency and Built Environment for Developing Countries. Advances in Science, Technology and Innovation.* eds C. Alalouch, H. Abdalla, E. Bozonnet, G. Elvin, and O. Carracedo (Cham: Springer). doi: 10.1007/978-3-030-10856-4_6

Jácome-Pólit, D., Santandreu, A., Rodríguez, A., Pinto, N., and Paredes, D. (2019a). "Quito' s resilient agrifood system," *ISOCARP Review 15*, (Amsterdam: ISOCARP), 271–296.

Jones, A. D., Creed-Kanashiro, H., Zimmerer, K. S., De Haan, S., Carrasco, M., Meza, K., et al. (2018). Farm-level agricultural biodiversity in the Peruvian Andes is associated with greater odds of women achieving a minimally diverse and micronutrient adequate diet. *J. Nutr.* 148, 1625–1637. doi: 10.1093/jn/nxy166

Lefebvre, H. (1978). *La vida Social en la Ciudad. De lo Urbano a lo Rural (1971)*. Barcelona: Península.

Long, N. (1996). "Globalización y localización: nuevos retos para la Investigación Rural," *En La Sociedad Rural Mexicana Frente al Nuevo Milenio. Sara Lara y Michelle Chauvet (Compiladores) Vol. I: La Inserción de la Agricultura Mexicana en la Economía Mundial*. México: Universidad Nacional Autónoma de México.

Maela (2011). "Hoja a hoja". *Boletín Digital Mensual del Movimiento Agroecológico de América Latina y Caribe, Edición Especial, No 4.* Available online at: http://www.maela-agroecologia.org/boletin-hojaa-hoja/

Maisels, Ch. (1993). *The Near East: Archaeology in the "Cradle of Civilization"*. London: Routledge.

Meerow, S., Newell, J. P., and Stults, M. (2016). Defining urban resilience: a review. *Landsc. Urban plann.* 147, 38–49. doi: 10.1016/j.landurbplan.2015.11.011

Mougeot, L. J. A. (1999). "For self-reliant cities: urban food production in a globalizing south," in *For Hunger-Proof Cities: Sustainable Urban Food Systems*, eds M. Koc, R. MacRae, L. J. A. Mougeot, and J. Welsh (Ottawa, ON: IDRC), 11–25.

Oviatt, K. (2016). *AGRUPAR y Empoderamiento: Informe de Resultados, Informe, Quito*. Universidad Colorado, Denver.

Papuccio de Vidal, S. (2011). *Mujeres, Naturaleza y Soberanía Alimentaria*. Buenos Aires: Librería de Mujeres Editoras.

Paredes, D. (2019). *Análisis Multiescalar del Éxito del Programa de Agricultura Urbana Participativa AGRUPAR como Medida de Adaptación ante el Cambio Climático en el DMQ*. Tesina, Quito: Facultad Latinoamericana de Ciencias Sociales.

Rodríguez, A. (2018). "Systems of Control for Agroecological Food Production and Commercialization in Quito, Ecuador," *RUAF Foundation, Urban Agriculture Magazine 33*.

Rodríguez, A., and Proaño, I. (2016). *Quito Siembra: Agricultura Urbana*. Quito: AGRUPAR, Conquito, Municipio del Distrito Metropolitano de Quito.

Santandreu, A., and Betancourt, O. (2019). *Trayectorias de Cambio, La gestión del Conocimiento para el Aprendizaje y el Cambio en la práctica*. Quito: Ecosad, Comunidad de Práctica sobre el Enfoque Ecosistémico en Salud Humana, Centro Internacional de Investigaciones para el Desarrollo, Ediciones Abya-Yala.

Santandreu, A., and Rea, O. (2016). "Qué ponemos en valor cuando vemos la ciudad con ojos de agricultura urbana? Acortando la brecha entre lo que miden los técnicos y lo que valoran las y los agricultores urbanos de El Alto (Bolivia)," in *Participación Social con Metodologías Alternativas desde el sur*, eds J. Astudillo, and T. Rodriguez-Villasante, (Quito: Universidad de Cuenca, Acordes/CEA y Abya Yala), 249–263.

Santandreu, A., and Rea, O. (2018). "La agricultura urbana, el derecho a la ciudad y el derecho humano a la alimentación: el Caso de El Alto, en Hacia la metamorfosis urbana," in *Apuntes Latinoamericanos para una Política de Ciudades,* (Cochabamba: CIAU; SEUR; Colegio de Arquitectos de Cochabamba; Colegio de Arquitectos de Bolivia), 215–238.

Santandreu, A., Rodríguez, A., Jácome-Polit, D., and Paredes, D. (2019). "From Urban Gardens to the Agri-Food Pact of Quito," in *Urban Agriculture Magazine,* 21–23.

Soja, E. (2001). *Postmetropolis: Critical Studies of Cities and Regions*. Oxford: Blackwell.

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EDITED BY
Rachel Bezner Kerr,
Cornell University, United States

REVIEWED BY
Caterina Batello Cattaneo,
Food and Agriculture Organization of the United Nations, Italy
Folarin Owagboriaye,
Olabisi Onabanjo University, Nigeria

*CORRESPONDENCE
Marta Astier
mastier@ciga.unam.mx

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Exploring the complexity of smallholders' intense use of glyphosate in maize crops from South Mexico: Remarks for an ongoing agroecological transition

Ana Sofía Monroy-Sais[1], Marta Astier[1]*, Germán Wies[2], Riccardo Pavesi[3], Daniel Mascorro-de Loera[4] and Luis García-Barrios[5]

[1]Centro de Investigaciones en Geografía Ambiental (CIGA), Universidad Nacional Autónoma de México (UNAM), Morelia, Mexico, [2]Instituto de Investigaciones en Ecosistemas y Sustentabilidad (IIES), Universidad Nacional Autónoma de México (UNAM), Morelia, Mexico, [3]Department of Political and Environmental Science (DESP), Faculty of Agro-Science, Study University of Milan, Milan, Italy, [4]Centro de Ciencias Básicas, Universidad Autónoma de Aguascalientes (UAA), Aguascalientes, Mexico, [5]Dirección Regional Sureste, Consejo Nacional de Ciencia y Tecnología (CONACYT), San Cristóbal de las Casas, Mexico

Recently, Mexico has launched policies of agroecological transition that seek to foster healthier agri-food systems. One of these policies is the reduction and eventual elimination of glyphosate by 2024. Despite being the most used herbicide in Mexico and the world, little information exists about what factors determine a greater or reduced use of glyphosate in different socio-ecological contexts. This study aimed to explore different agricultural management, biophysical and social variables and their effects on glyphosate use in maize crops by smallholders (<8 ha). A questionnaire and semi-structured interviews were performed with 142 farmer families in four regions of the state of Chiapas to document the use of herbicides and glyphosate. By using regression trees, we identified those variables that determine a greater or lesser use of glyphosate for each region and jointly. The average volume of glyphosate for the four regions during an agricultural cycle was 2.7 l/ha^{-1}. Sets of variables were associated with syndromes of greater use of glyphosate and herbicides in general, such as small plots (<0.67 ha), indigenous population, younger farmers, fewer family members, rainfed conditions, and plots without mechanization. These results can help the design of contextualized and flexible policies of transition, consistent with the socio-ecological heterogeneity of Mexico.

KEYWORDS

glyphosate, milpa, paraquat, Chiapas, annual crops, agroecological transition, 2,4-D Amina

Introduction

Efforts directed toward having more resilient and sustainable agri-food systems are currently considered a worldwide priority (Food Agriculture Organization, 2018; Wezel et al., 2020). Mexico has launched a series of policies to move in this direction and foster healthier agri-food systems. Among these policies, the gradual reduction and the prohibition of the herbicide called glyphosate have been raised. In response to the available evidence regarding the effects to human health and ecosystems, in 2015 the World Health Organization (WHO) and the International Agency for Research on Cancer (IARC) reclassified glyphosate as a "probable carcinogen for humans" (International Agency for Research on Cancer, 2017). In December of 2020 in Mexico, a presidential decree was issued that prohibits the use of this agrochemical starting in 2024 and the supposed staggered elimination of the same starting from 2021. The decree likewise prohibits the planting of transgenic maize and urges the creation of scientific research that helps transition toward "sustainable and culturally adequate alternatives" (DOF, 2020). Mexico is not the first country to implement measures like these and recognize the toxicity of this herbicide, in addition to establishing the need to put into practice alternatives for its use (PAN, 2018; Malkanthi et al., 2019; Beckie et al., 2020; CONACYT, 2020; MacLaren et al., 2020; Ramírez Muñoz, 2021).

On a worldwide scale, the use of glyphosate has increased by 1,500% since 1996 (Clapp, 2021). Mainly, this increase was because of the commercialization and the sowing of genetically modified crops tolerant to glyphosate, as well as the release of its commercial patent in 2000 (CONACYT, 2020). Currently, approximately 56% of the global use of glyphosate in agriculture is destined for transgenic crops (Benbrook, 2016). Nevertheless, it has also been found that glyphosate has managed to penetrate peasant and small-scale agriculture (Mariaca-Méndez et al., 2007; Bernardino et al., 2016; Mascorro-de Loera et al., 2019). In the case of Mexico, even though transgenic crops on the commercial scale are banned, the use of glyphosate has been widely adopted. At the national level ∼60% of the open-air farmers use chemical herbicides in their production (INEGI, 2019). Glyphosate is the pesticide with the highest import volumes at the national level; however, there is no information on how it is distributed and used in the country (Instituto Nacional de Ecología y Cambio Climático et al., 2020). It has been identified that glyphosate is used for diverse crops, underscoring its application to maize with 35% of the total national use (Alcántara-de la Cruz et al., 2021).

Maize is the most important crop in terms of human consumption and for the volume of production in Mexico (Sweeney et al., 2013). Smallholders contribute around 50% of the national production of such a crop (Puyana, 2012; González-Ortega et al., 2017), in addition to supporting self-sufficiency to millions of peasant families and for diversifying their livelihood options (Bellon et al., 2018). Mexico it's the center of origin and domestication of maize, dating from 6,000 to 10,000 years ago (Perales and Golicher, 2014). Traditionally, maize cropping by smallholders was associated with the system called "milpa," which involved little use of external inputs, the use of native seeds or landraces, polyculture, and little or no mechanization (Toledo et al., 2003; Bellon et al., 2018). During the last decades, this type of production has experienced drastic changes. Much of the labor has been mechanized, and the use of agrochemicals has been generalized (Vigouroux et al., 2011). In particular, the use of manual means of weed control has been substituted by herbicide application (Vázquez et al., 2004; Parsons et al., 2009; McClung de Tapia et al., 2014).

Even though different agroecological alternatives exist for weed management (Liebman et al., 2004; PAN, 2018; CONACYT, 2020; MacLaren et al., 2020; Ramírez Muñoz, 2021), various factors have encouraged the increasingly greater use of chemically synthesized herbicides and glyphosate (Desquilbet et al., 2019; Anaya-Zamora et al., 2020; Clapp, 2021). In Mexico, historically, the countryside policies have promoted the adoption of technology packages associated with the use of improved maize varieties and agrochemicals (Bellon and Hellin, 2011). These agrochemicals are frequently imposed as part of agricultural subsidies to farmers. The role of national and international agribusiness in this strong adoption has been key, partnering with different government agencies. On the other hand, the North American Free Trade Agreement (NAFTA) since 1994, also promoted a massive migration of peasants to urban centers or the United States by creating a collapse in maize prices (García-Barrios et al., 2009; Puyana, 2012). Those who continued their production—above all market-driven—resorted to the application of chemically synthesized herbicides with backpack sprayers that implied a decrease in human labor and an investment in time. Currently, the scarce availability of a workforce in the countryside affects practices like manual weeding (Keleman et al., 2009). Herbicide adoption is also influenced by biophysical conditions of the plots, such as hillside agriculture where mechanized labors are limited and soil conditions that favor weed growth (Beckie et al., 2020).

To reverse this dependence on the use of glyphosate and of chemically synthesized herbicides in general, it is necessary to understand how this complex ensemble of agricultural management, social, and biophysical conditions act favoring or diminish their use. In this sense, the objectives of this study are: (i) to make an agronomic characterization of the use of glyphosate and other herbicides in maize crop systems by smallholders; and (ii) to identify sets of variables (management, social, and biophysical) that explain the variability in the volume application of glyphosate specifically. We develop our research in the state of Chiapas in southern Mexico, which possesses a great ethnolinguistic, ecological, and biophysical diversity, as well as native maize varieties (Brush and Perales, 2007). Although various factors can affect high or low glyphosate and herbicides use by farmers (Colbach et al., 2020), it is possible to identify groups of characteristics or syndromes that can result in greater use of glyphosate and/or herbicides in general. These syndromes can help us to understand the needs of different groups of farmers for a transition to not using glyphosate. Although we focus on glyphosate because its ban is approaching in the coming years, we explore the use of other herbicides, since it has been documented the use of various herbicides in the region (Bernardino et al., 2016; Mascorro-de Loera et al., 2019). This research strives to contribute information to create agroecological alternatives for the use of glyphosate within the context of a country with great socio-ecological heterogeneity like Mexico.

Materials and methods

Study site

Our research employed a case study design with aggregated units (Yin, 2003), the units represent four municipalities of different socioeconomic regions within the state of Chiapas (Figure 1). The state of Chiapas is among the five largest maize producers in Mexico, mostly by smallholders' production in rainfed areas (Eakin et al., 2015). In Chiapas, for more than 60 years, the use of agrochemicals (fertilizers, herbicides, and insecticides) has been promoted through different programs and government supports (Bellon, 1991; Eakin et al., 2014). Chiapas poses high levels of poverty, around 75% of its population is considered in a condition of poverty (CONEVAL, 2020). The selected regions have a high ecological and cultural value, with the presence of different indigenous groups, many of whom plant maize as part of their livelihoods. Some of the common characteristics among regions is that all farmers plant maize for the double purpose of self-consumption and selling the surpluses to the market. The use of improved varieties started in the 1960s, accompanied by the introduction of fertilizers, herbicides and pesticides (Bellon, 1991; Arellano-Monterrosas et al., 2002), yet many farmers still plant *criollo*[1] seeds. Most of the regions have tropical weather, except for the Altos region that has temperate weather. Next, each of the regions are described, and some important characteristics are indicated in Table 1. Photographs of the representative maize plots in the four regions appear in Figure 2.

The Valleys region's main economic activity is agriculture where seasonal crops are grown. Within the region, we worked in the municipality of Ocozocoautla in valley areas (VO). Within this municipality, five locations were selected, two of them (Aguacero and Lázaro Cárdenas) with a mostly Tzotzil indigenous population. In the remaining three locations, the population is considered *mestizo*[2] (Ignacio Zaragoza, Galeana and San José). The altitude of the sampled plots ranges from 680 to 960 m. Most of the land is rainfed with some exceptions of irrigated land. The soil is mainly rocky limestone, creating rugged slopes not appropriate for mechanized agriculture. Planting in polyculture is common, where maize, bean and squash are the most common crops; cattle raising is also practiced.

The Frailesca region is characterized by the presence of annual crops, coffee plantations, along with cattle raising (Cortina-Villar et al., 2012). Within the Frailesca region, the study was developed in the municipality of Villaflores (SV), specifically in mountainous areas part of the La Sepultura Biosphere Reserve (LSBR). Data from three localities was obtained: California, Tres Picos and Tierra y Libertad. The three localities have a predominantly *mestizo* population (Cortina-Villar et al., 2012). The altitude of the sampled plots ranges from 865 to 1,243 m. The plots were situated behind the forest limit of the LSBR, which possess a high slope not suitable for mechanized agriculture. Mostly seasonal agriculture is practiced, with some exceptions to irrigation agriculture. Planting in polyculture is common, where maize, bean and squash are the most common crops. After the harvest, the stubble is used for livestock.

In the Altos region, agriculture and temporary or permanent migration are the predominant activities, with maize, bean, squash and coffee as the main crops (Maldonado-López et al., 2017). Within the Altos region, the study was developed in the municipality of Amatenango del Valle (AV) in the locality of the same name, with indigenous Tzeltal families. The use of native maize varieties or *criollo* varieties has been maintained by the population in AV. Nevertheless, there is a high dependence on agrochemicals such as herbicides and fertilizers (Bernardino et al., 2016). The studied plots have an average altitude of 1,808 m located in stepped plateaus with shallow and rocky soil, which are inadequate for mechanized agriculture. The agriculture of AV is mainly rainfed with few irrigated plots supplied from nearby springs. The farming activities (sowing, weeding, agrochemical application and harvesting) are mostly supported by social relationships among relatives and close friends. Due to population growth, the size of plots of land for each family unit has decreased and its use is intensive and continuous year after year without rest.

The agricultural activities in the Selva region are mainly maize cultivation, cattle ranching and more recently oil palm plantation (Zermeño-Hernández et al., 2016), these activities are strongly influenced by the people's place of origin (Wies et al., 2022). The maize crop systems studied belong to

1 *Criollo* maize or seeds refer to different types of seeds that farmers can plant, manage, and select without having to purchase them. These include landraces or native seeds passed from generation to generation, and *acriollados* or creolized seeds which represent mixtures of modern improved varieties and landraces (Bellon et al., 2006).

2 *Mestizo* refers to people with mixed ethnic race that do not self-defined as belonging to an indigenous ethnic group.

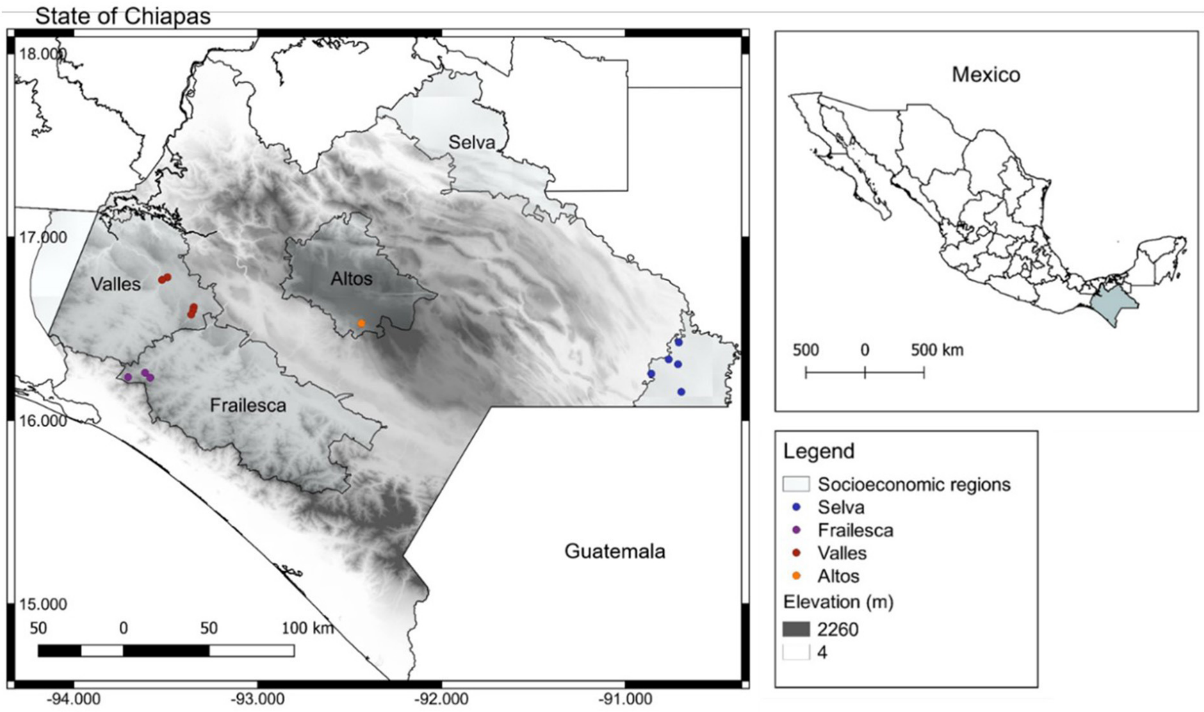

FIGURE 1
Map of the location of the state of Chiapas and the four socioeconomic regions studied.

TABLE 1 General characteristics of the regions and localities within the study site.

Municipality and study region	Socio-economic region	Localities	Altitudinal range	Households/ plots	Ethnic origin
Ocozocoautla—Valles de Ocozocoautla (VO)	Valles	Galeana, Ignacio Zaragoza, San José, Aguacero (A), Lázaro Cárdenas (LC) (5)	680–960 m	41	Indigenous Tzotzil (A and LC) and *mestizo*
Villaflores—Sierra de Villaflores (SV)	Frailesca	Tierra y Libertad, Tres Picos, California (3)	865–1,193 m	37	Mainly *mestizo*
Amatenango del Valle (AV)	Altos	Amatenango del Valle (1)	1,850–2,100 m	32	Indigenous Tzeltal
Marqués de Comillas (MC)	Selva	Quiringuicharo, Zamora Pico de Oro, La Victoria, San José, Reforma Agraria (5)	96–219 m	32	Mainly *mestizo*

the municipality of Marqués de Comillas (MC). Marqués de Comillas adjoins the Montes Azules Biosphere Reserve. The studied locations were: Reforma Agraria, La Victoria, Quiringuicharo, Zamora Pico de Oro, and Barrio San José. The most frequent soils are alluvial plains and low sandstone hills (Wies et al., 2022), some of these are adequate for the mechanized agriculture. The maize crop systems are small scale (1–5 ha) with both hybrid and *criollo* varieties and the use of chemical inputs, such as fertilizers, herbicides, and insecticides are widespread.

Methodological approach and data collection

The data collection in each region originally comes from other studies, mainly the realization of postgraduate theses. For all the locations, permission from the ejidal authorities was sought to undertake the different studies. The methods included conducting semi-structured interviews and questionnaires with the farmers. All the plots of maize crops were visited in the cases of SV, VO, and MC to record coordinates, altitude, slope,

FIGURE 2
Fields and maize crops in four regions. **(A)** The VO region, plot in rocky soil; **(B)** the SV region, plot after the maize harvest; **(C)** the AV region, plot with a variety of *criollo* maize and herbicide application by the family; **(D)** The MC region, plot with mechanization in the maize harvest. Credits: **(A)** Sofia Monroy; **(B)** Riccardo Pavesi; **(C)** Daniel Mascorro; and **(D)** Carolina Berget.

and associated crops. In the case of AV, periodic visits to 10 plots were performed during the agricultural cycle conducting participant observation. The data was collected in different years for each region: VO in 2019, SV and MC in 2018, and 2016 for AV; during the spring-summer cycle. The interviews were performed directly by the authors to the farmers and heads of families with free, previous, and informed consent. The selection of participants was random and subsequently voluntary at all sites, with the prerequisite that they had a maize crop for the agricultural cycle studied.

The information collected in all the sites documented the general use of inputs in maize crops, including sociodemographic and agricultural management data from the farmers and their families. Afterwards, a database was constructed with 78 variables and qualitative information required for the analysis and interpretation of herbicide and glyphosate use. Plot level data were standardized to one hectare for comparisons. The volumes of the different herbicides also standardized to express liters of formulated ingredients in their commercial form. The names of the herbicides and the active ingredients were validated by the farmer or later with regional information about agrochemicals' use (Bernardino, 2013).

Data analysis

For the agronomic characterization of the glyphosate use we employed descriptive statistics for variables, such as herbicide volume (glyphosate, 2,4-D, and paraquat), the moment of application, wages, and seed type, among others. In order to delineate the different glyphosate use profiles and to identify the variables that establish differences between these profiles, regression trees analyses were carried out, for each region independently and jointly. The regression tree method allows the binary and recursive partition of a response variable (in our case glyphosate volume) under the control of a set of both categorical and quantitative explanatory variables (Borcard et al., 2011). The result is a tree with "leaves" or terminal nodes that are comprised of a subset of observations that minimize the variation within each group and maximize it among groups (Borcard et al., 2011).

To construct the regression trees, firstly, those variables that could generate an effect in the use of herbicides and glyphosate were selected. In total 21 variables were analyzed: 20 explanatory variables in response to the volume of glyphosate variable. The first regression tree included all four regions with 142 observations given by each plot and farmer. Afterwards, each of the regions was analyzed separately, constructing an independent regression tree to identify variables that could be masked in the analysis at the macroregional level.

Afterwards, some of the important variables in the regression tree of all the regions were selected to explore relationships with the volume of glyphosate and generate sets of predictors performing different tests. ANOVAs were used to see differences in categorical variables like water regime (rainfed, irrigated, river influence) for example. *T*-tests were employed for binary variables like if crop rotation is practiced or not, for example. Linear regressions were used to explore relationships between continuous variables and the volume of glyphosate, like the volume of other herbicides, for example. To assess the significance and the effect of the explanatory variables in the variation of the glyphosate volume (or R^2-values), linear models were adjusted. All the analyses were performed following basic routines in R statistical program version 3.6.1 and Rstudio version 1.2.5019 (R Core Team, 2019).

Results

Agronomic characterization of herbicides and glyphosate use in maize crops

Farmers managing the studied maize crop systems reported that the use of glyphosate is mostly given in the pre-emergence states (Figure 3); in some cases, it was applied post-emergence between the rows. In the case of AV, it was used almost exclusively post-emergent to the crops but in early vegetative stages. It is common that farmers combine glyphosate with the herbicide 2,4-D in the same application. Seven commercial names were registered for glyphosate from the surveys; nevertheless, one brand predominates in 60% of the cases. In 2019, the average cost of this commercial brand of glyphosate in the studied regions was 110 Mexican pesos per liter (around 5.5 USDs), farmers reported. This price was very similar to the other two most used herbicides: 2,4-D and paraquat.

With respect to other weed management strategies, 54% of the farmers resort to manual weeding using tools like the machete and hoe. The use of manual weeding is concentrated in the AV and SV regions, although this is usually not sufficient to control the weeds during a complete agricultural cycle and

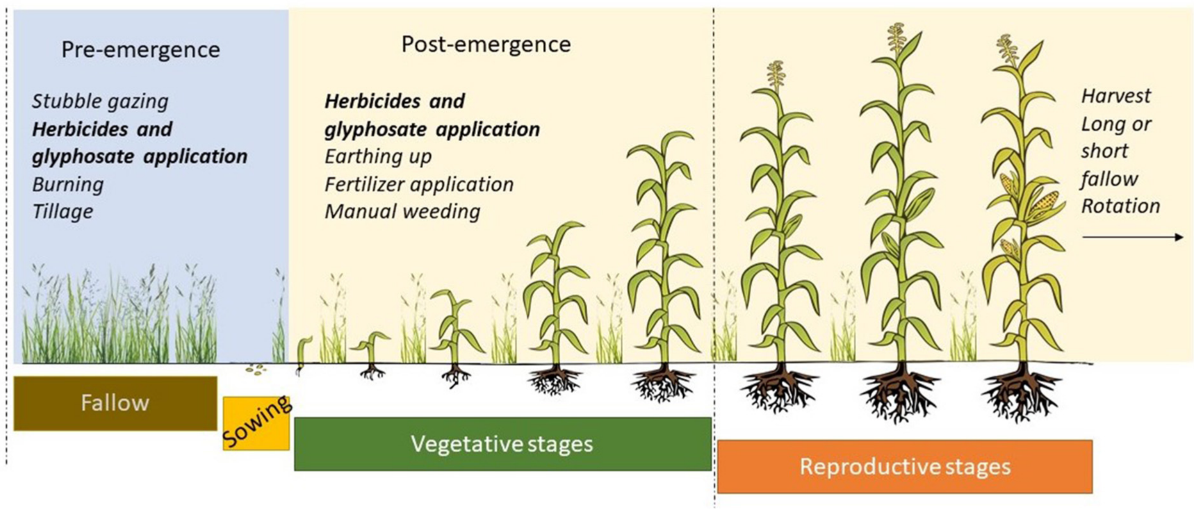

FIGURE 3
Main management practices in each stage of the maize productive cycle and moments of herbicide and glyphosate application. Not all the practices are performed in all the plots.

TABLE 2 Average volumes of the different herbicides per hectare in an agricultural cycle for each region.

	VO	SV	AV	MC	Total by herbicide
Gylphosate (l/ha^{-1})***	3.2 (1.8)[a]	2.8 (2.3)[a]	3.6 (2.0)[a]	0.8 (1.5)[b]	2.7 (2.2)
2,4-D (l/ha^{-1})***	3.2 (1.4)[a]	3.8 (3.6)[a]	2.4 (1.8)[a]	0.1 (0.4)[b]	2.5 (2.5)
Paraquat (l/ha^{-1})***	3.4 (1.8)[a]	4.3 (3.2)[a]	4.4 (2.7)[a]	0.7 (0.9)[b]	3.3 (2.7)
Total by region (l/ha^{-1})***	9.4 (3.9)[a]	11.3 (6.4)[a]	10.3 (4.8)[a]	1.6 (1.6)[b]	8.4 (5.9)

Total volumes by region can be higher than the sum of three herbicides because other lesser used herbicides exist. ***Significantly different values with $p < 0.001$. The letters indicate those groups that differ among themselves.

most of the farmers also apply herbicides. From a total of 93 plots, data were obtained about daily wages dedicated to weed control (both manual and with herbicides). Among them, the average of daily wages dedicated to this task is 5 per hectare per agricultural cycle. Nevertheless, this quantity varies greatly and can reach 24 wages. These daily wages are performed by family members or relatives, otherwise they are paid, the cost of a daily wage is between 100 and 150 Mexican pesos. Other common practices before and after the sowing of maize in the studied plots are shown in Figure 3.

The main herbicides used were paraquat, followed by glyphosate, and then by 2,4-D (Table 2). In 86 of the studied plots (60.6%), these three herbicides were applied during the studied agricultural cycle. In 22 of them, only two herbicides were used (15.5%) and in 24 only one herbicide (16.9%). Of the total sample, only 10 farmers (7%) did not use any herbicide. The region that uses the largest total volume of herbicides is SV. The herbicide applications per agricultural cycle can vary between 1 and 4 applications. Other herbicides used less frequently are saflufenacil, ametryn, lodosulfuron, and topramezone. The use of herbicides and glyphosate did not differ significantly among the plots cultivated with *criollo* maize from those planted with hybrid maize. The only region that shows significant differences in the use of the three herbicides is MC, with much smaller volumes that the other three regions (Table 2).

Management, biophysical, and social determinants in glyphosate use

The results from the regression tree differentiates 5 groups of farmers (terminal nodes) with a range of glyphosate use from 1.1 to 4.2 l/ha^{-1}, and an average of 2.7 l/ha^{-1} (Figure 4). The group with lower volumes of glyphosate use is determined by farmers using also lower volumes of the 2,4-D herbicide ($<$ 0.85 l/ha^{-1}). Other variables that are also associated with this group include plot altitudes lower than 449 m, water regime determined by river floodplain influence, and use of lower volumes of the paraquat herbicide ($<$ 0.5 l/ha^{-1}). This first group on average uses 1.1 l/ha^{-1} of glyphosate and is comprised of 40 farmers. The following group in terms of lower glyphosate use is characterized by having opposite values from the previous group. In addition to plots larger than 0.67 ha, in altitudes higher than 814 m, they use manual weeding methods and plant in polyculture to a lesser extent ($<$ 2 associated crops). The group who uses the greatest quantity of glyphosate (4.2 l/ha^{-1}) is compose by farmers who likewise use greater volumes of 2,4-D ($>$0.85 l/ha^{-1}) and paraquat ($>$ 0.5 l/ha^{-1}). Furthermore, they plant in rainfed conditions, irrigation, or with residual moisture in plots above 449 m with $<$0.67 ha of extension. This group is comprised by 20 farmers. Other characteristics that determine greater use in glyphosate are the non-use of manual weeding, plots without fallow periods, intercropping maize, and the indigenous origin of the farmer.

In Table 3, the ranking of important variables associated with an increase or decrease in glyphosate use is shown. Variables positively associated with greater volumes of glyphosate in general are greater volumes of the 2,4-D and paraquat herbicides; the plots' higher altitude; the rainfed, irrigation, and residual moisture water regimes; and the belonging to an indigenous ethnic group. Some of the variables that generate a negative effect with the volume of applied glyphosate are as follows: crops with river floodplain influence, larger plots, plot rest or longer fallow periods, no intercropping, performing manual weeding practices, and larger family units. These and other variables are explored in more depth in the Supplementary material.

Identification of groups with greater glyphosate use in different regions

The summarized results from the regression trees that were constructed for the different regions are shown in Table 4. For region VO, the group with the highest glyphosate use is comprised of farmers younger than 43 years old (4.6 l/ha^{-1}), who form a group by themselves (terminal node). Conversely, the older farmers over 43 years old, who also use *criollo* or native maize seeds, are the group who use glyphosate the least (1.8 l/ha^{-1}). In an average range, there are the 43-year-old or older farmers, who use hybrid seeds, and use fewer than 3.5

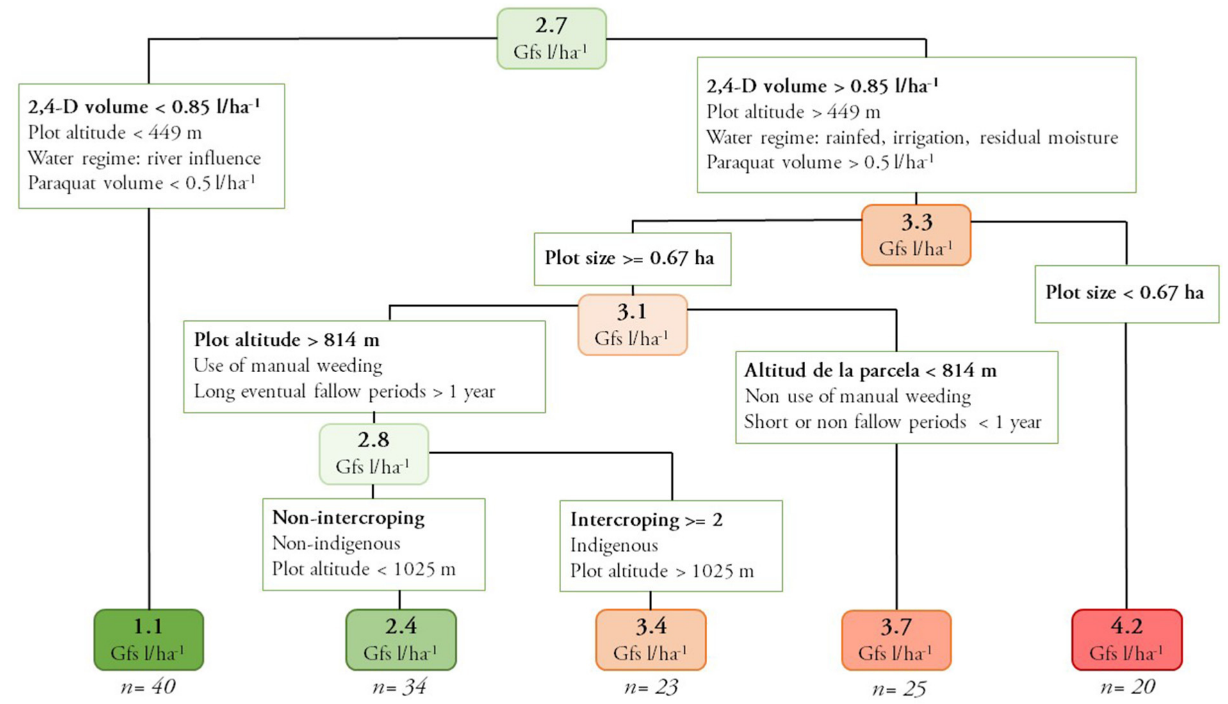

FIGURE 4
Regression tree of the joint regions and their 5 terminal nodes or groups. Relative error = 0.71, or fraction of the variance not explained by the regression tree (1–R^2). Inside the white boxes, the main variables that define the separation from the groups are shown in bold, and with standard letters the substitute variables, which have a behavior similar to the main variables, although they do not separate the groups. The colored boxes indicate the average values of the response variable (volume of glyphosate in liters/ha^{-1}) and if these are low (green) or high (orange) values.

TABLE 3 The most important variables in the construction of the regression tree and its effect on the increase or decrease in glyphosate use.

Explanatory variable	VI*	Variable state	Effect in glyphosate
Herbicide 2,4-D volume (l/ha^{-1})	30	Continuous	+
Plot altitude (m)	20	Continuous	+
Water regime	12	Rainfed, irrigated, soil moisture	+
		River floodplain	-
Plot size (ha)	10	Continuous	-
Plot rest or longer fallow periods	10	Yes	-
		No	+
Herbicide paraquat volume (l/ha^{-1})	9	Continuous	+
Associated crops (intercropping)	4	Discrete	+
Belong to an indigenous ethnic group	3	Yes	+
		No	-
Practice manual weeding	1	Yes	-
		No	+
Size of the family unit	1	Discrete	-

*VI refers to the variable importance for the construction of the regression tree, the total sum the 100% importance. The colors of the explanatory variables indicate if they are management (purple), biophysical (green) or social variables (brown) (inspired in Colbach et al., 2020).

l/ha^{-1} of 2,4-D herbicide. On average, this group uses 2.7 l/ha^{-1} of glyphosate. Finally, farmers with the same characteristics as the previous group but who use quantities >3.5 l/ha^{-1} of 2,4-D herbicide, form a group that uses on average 4.1 l/ha^{-1} of glyphosate. This group is the second that uses higher volumes of glyphosate.

In the SV region, the group who use the most glyphosate is formed by farmers with plots under 0.9 ha and who also have

TABLE 4 Summary of the regression trees of each region: number of terminal nodes, the main explanatory variables, average values of the response variable (l/ha^{-1} of glyphosate), and the percentage of the regional sample within each terminal node.

	Terminal node	Explanatory variables*		Glyphosate l/ha^{-1}	% of *N*
		Split variable	Terminal node variable		
VO	1	–	Age < 43 years	4.6	32
RE = 0.58	2	Age ≥ 43 years	Criollo seed	1.8	32
	3	Age ≥ 43 years; Hybrid seed	2,4-D < 3.5 l/ha^{-1}	2.7	22
	4	Age ≥ 43 years; Hybrid seed	2,4-D > 3.5 l/ha^{-1}	4.1	15
SV	1	Plot size < 0.9 ha	Family members < 5	5.2	27
RE = 0.56	2	Plot size < 0.9 ha	Family members ≥ 5	2.2	14
	3	Plot size ≥ 0.9 ha	Yield > 2.5 ton/ha^{-1}	2.4	27
	4	Plot size ≥ 0.9 ha	Yield < 2.5 ton/ha^{-1}	1.4	32
AV	1	–	Family members < 5	4.5	41
RE = 0.72	2	Family members ≥ 5	Paraquat > 4.6 l/ha^{-1}	4.2	22
	3	Family members ≥ 5	Paraquat < 4.6 l/ha^{-1}	2.2	38
MC	1	Paraquat < 0.23 l/ha^{-1}	Rainfed	2.4	16
RE = 0.75	2	Paraquat < 0.23 l/ha^{-1}	River floodplain	0.8	38
	3	Paraquat ≥ 0.23 l/ha^{-1}	Age < 51 años	0.7	16
	4	Paraquat ≥ 0.23 l/ha^{-1}	Age ≥ 51 años	0.1	31

RE, Relative error or variance fraction not explained by the tree. *The explanatory variables are read consecutively for each region. For example, in the VO region in node 4 refers to: 43-years-old farmers or older, using hybrid seeds, and applying more than 3.5 l/ha^{-1} of 2,4-D herbicide.

family units with fewer than five members. The average volume that this group uses is 5.2 l/ha^{-1} of glyphosate. Farmers with the same sized plots but with more than five family members, use on average up to tree liters less of glyphosate per hectare than the previous group. Another group is comprised by farmers with larger plots (>0.9 ha) and with yields >2.5 tons per hectare. This group on average use 2.4 l/ha^{-1} of glyphosate. Finally, the group with the lowest glyphosate use is comprised by farmers with 0.9 ha plots or larger and with yields <2.5 ton/ha^{-1}, with an average use of 1.4 l/ha^{-1} of glyphosate.

For the AV region, the group that uses more glyphosate shares one of the same characteristics with the group that most uses glyphosate in the SV region i.e., families composed of fewer than five members. On average, this group use 4.5 l/ha^{-1} of glyphosate. This group represents little more than one third of the sample in the region. The following group is formed by farmers with families of five members or more and using on average volumes of paraquat higher than 4.6 l/ha^{-1}. This group on average uses 4.2 l/ha^{-1} of glyphosate. The last group, who uses less glyphosate in the region (2.2 l/ha^{-1}), differs from the previous one by using <4.6 l/ha^{-1} of paraquat, which shows the reciprocal relationship that exists between these two herbicides.

Farmers in the MC region use the least glyphosate and herbicides of the four regions. Within this region, the group using more glyphosate (2.4 l/ha^{-1}), on the other hand, uses less paraquat (<0.23 l/ha^{-1}). This group also sows under rainfed conditions. The second group also uses volumes of paraquat <0.23 l/ha^{-1} but sow in river floodplain condition, using only 0.8 l/ha^{-1} of glyphosate. For their part, the farmers that use 0.23 l/ha^{-1} or more of paraquat and are younger than 51 years, use on average 0.7 l/ha-1 of glyphosate. Finally, the group that uses glyphosate the least is characterized by using paraquat in the same quantities as the previous group, but the farmers are 51 years or older. This group uses volumes of only 0.1 l/ha^{-1} on average. In this region the herbicide paraquat has an antagonistic relationship with glyphosate contrary to the AV region (Supplementary Figure 4).

Discussion

The different profiles of glyphosate use show that certain biophysical, social, and management characteristics are determining a greater or lesser use in the studied areas. No single factor or characteristic (biophysical, social, or management) is determining by itself a greater use of glyphosate, but instead a complex series of factors determine glyphosate use together. These characteristics result in what we call "syndromes of greater or lesser use." The syndrome of greater use is associated with small production units (<0.67 ha), an indigenous origin population, younger farmers, small family units, land in rainfed conditions, and without the possibility of mechanization. This syndrome also entails positive associations with the other two most used herbicides in the regions: 2,4-D and paraquat. That is to say, this syndrome is for synthetic herbicides use in general. For its part, the syndrome of lesser use is associated with larger production units (>0.67 ha), in river floodplain terrains, larger family units, older farmers, longer fallow periods, crop rotations, use of manual weeding, and mechanized plots. We discuss some of the implications, opportunities, and policy considerations for the glyphosate phase-out and agroecological transition for these different types of smallholders.

The use and abuse of glyphosate, 2,4-D and paraquat

Our results show that farmers who apply higher volumes of glyphosate, also apply more 2,4-D and paraquat, and in three of the four studied regions the volumes used are statistically the same. Regarding glyphosate use, the volumes used are found within the range reported by industrial agriculture (Arellano-Aguilar and Rendón von Osten, 2016; CONACYT, 2020). Nevertheless, the variability within the sample (0–10 l/ha^{-1}) shows farmers that currently have a high dependence on herbicide and others that manage to crop without using it. For those who use glyphosate and 2,4-D dissolved in the same solution to control a wide spectrum of weeds (i.e., monocots, broadleaf, annuals, and perennials), during the pre-emergence crop stage, a possible antagonism could be producing the opposite effect on the weed control (Li et al., 2020). Another important aspect for discussion is the possible development of resistance to these three herbicides by the regional weed communities, which could trigger increasingly greater use of these herbicides. Such a phenomenon has been recorded in different parts of the world, where over the last years, the resistance of many weeds to glyphosate has increased, gradually reducing its effectiveness (Beckie, 2011; MacLaren et al., 2020).

Faced with the suppression of glyphosate, it is possible that the farmers who already know this triad of herbicides could just increase the use of 2,4-D, paraquat, or other synthetic herbicides. This scenario is possible if they do not know about viable agroecological alternatives and it is dangerous since paraquat, for example, is considered an even higher toxic herbicide in relation to glyphosate (Bernardino et al., 2016). This scenario of input substitution was documented in Sri Lanka, in conjunction with rising herbicide costs during the glyphosate ban (Malkanthi et al., 2019). For this reason, we consider important a policy that monitors the prices of inputs in this transition stage and rapidly mobilizes the agroecological alternatives across the country.

Social and land tenure characteristics in glyphosate use

The social and land tenure characteristics that are associated with the syndrome of higher glyphosate use are the following: (a) the size of the production unit—smaller areas, higher volumes of glyphosate; (b) ethnic origin—the indigenous population tends to use greater volumes; (c) the size of the family—in some regions the smaller families use higher volumes, and d) the farmers' age—younger farmers tend to use higher volumes. These results agree with those found by Bernardino et al. (2016) in a study where the factors that explain pesticide use for different crops, including maize, in three municipalities in the Highlands of Chiapas were characterized. Like our results, these authors found that in smaller plots a more intensive use of the land is made, using large quantities of pesticides. In addition, one explanation of the high pesticide use and the ethnic origin relates to their functional illiteracy of the Spanish language because their native language is Tzotzil or Tzeltal, creating difficulty to follow the herbicides labels' recommendations, and the model of the Green Revolution in which they learned to manage crops since an early age (Bernardino et al., 2016).

Our results show that the younger smallholders generally use larger volumes of glyphosate, mainly in the VO and MC regions. Many farmers of productive ages migrate to other cities as a temporary strategy for obtaining complementary income, without abandoning farming activities (Pacheco-Ladrón de Guevara, 1999). In the VO and AV regions, the seasonal-type migration and working outside the countryside considerably affect the time available for practices like manual weeding, creating an excessive use of agrochemicals (Keleman et al., 2009). In the state of Chiapas, a large proportion of the maize farmers depend on other income sources outside the countryside (Eakin et al., 2015). We believe that using large amounts of glyphosate for weed control is a strategy resorted to by some of the younger farmers for longer periods of absence from the field. On the other hand, older age is usually associated with having traditional and ecological knowledge, affecting management decisions and the use of inputs in maize cultivation (Bellon and Hellin, 2011). Our interpretation is that some older farmers can bare certain knowledge for weed management that is unrelated to the use of synthetic herbicides and glyphosate, leading to less use.

The size of the family nucleus, and therefore the members' participation in the farming activities that sustain the farmer economy (Maldonado-López et al., 2017), influences the quantity of applied herbicides in the maize crop, which is evident in the cases of AV and SV. This result responds to the need for workforce for crop maintenance and, if there is no workforce, large quantities of herbicide are usually applied to save time and effort (Chikoye et al., 2004). Another problem related to the composition of the family unit and the use of herbicides refers to child labor in fieldwork. This problem has been documented in the SV region (Pavesi, 2018), either to teach them how to farm or to reduce the need for paid day workers. This implies that these minors are exposed to a great quantity of agrochemicals, like glyphosate, at a very early age, increasing the possibility of intoxication and other health problems caused by high occupational exposure (CONACYT, 2020).

Management practices and plot characteristics in the use of glyphosate

Our results show that less glyphosate use is positively associated with management practices such as crop rotation and longer fallow periods (Supplementary Figures 9, 10). Crop rotation, including cover crops, has been commonly associated with a lower incidence of weeds and a reduction in synthetic herbicide use with important environmental benefits (Hunt et al., 2017; Rosenzweig et al., 2018; Adeux et al., 2019). Regarding fallowing and its association with lower glyphosate use, we believe that this result is related to the maintenance of more diverse weed communities in crop plots, which generate less competition (Storkey and Neve, 2018) in contrast to homogenous weed communities dominated by few but very aggressive weeds.

In the high-altitude zones (i.e., AV, VO, and SV) greater use of glyphosate and herbicides, in general, are found. These regions are associated with no possibility of mechanization and steep slopes. Conversely, in the MC region, with altitudes lower than 500 m, where mechanization is possible, fewer quantities of glyphosate are used. In areas of steeper slopes conditions are prone to runoff and erosion, which provoke the reduction of glyphosate and other herbicides' effect (Borggaard and Gimsing, 2008; Todorovic et al., 2014; Richards et al., 2018). In addition, these conditions create difficulties for performing manual weeding (Pavesi, 2018). Particularly, in the SV region, where the soils possess a predominantly sandy texture, glyphosate absorption might be low and leaching high (Borggaard and Gimsing, 2008; Todorovic et al., 2014).

Another finding of this study shows that the condition of humidity (i.e., rainfed, irrigated, residual moisture, and river floodplain influence) affects glyphosate use, being the rainfed condition that leads to greater use. This mainly contrasts with the river floodplain influence in the MC region. Seasonal floods could control the weeds, at least in the pre-planting stage, decreasing the necessity for applying glyphosate at this moment (Carey et al., 2015). Nevertheless, the behavior of weeds in river floodplain or irrigation systems has been poorly explored in contrast to rainfed systems in maize crops. In rainfed systems, weed growth aligns with the crop's emergence, causing the smallholders to resort to greater use of glyphosate, above all in pre-emergent stages to reduce the competition in the emergent stage. Understanding the different stages in the life cycle of weeds and their ecological pressures—for example, seed predation, hydric stress, pathogens, or herbivory—(MacLaren et al., 2020), can help the design of agroecological alternatives for weed control, especially for rainfed maize systems.

Our results also show that in plots where intercropping is established (mainly maize, bean, and squash) an unexpectedly greater amount of glyphosate is used. In the studied regions, usually, the planting of beans and squash is delayed with respect to maize, resulting in a larger number of herbicides applications in the pre-and post-emergence stages (Pavesi, 2018). In addition, this practice is often linked to the use of other herbicides like 2,4-D that have a different action than glyphosate. This condition can lead to a greater application of glyphosate in plots with intercropping. Nevertheless, for generating stronger statements, studies directed toward understanding this phenomenon should be performed because this could be a "mirage" effect of other characteristics associated with the region such as plot size and ethnic origin. What can be demonstrated is that, even in a traditional system like milpa, closely associated with self-consumption, farmers use large quantities of glyphosate and herbicides.

On the other hand, in the studied regions (except AV, which had no yield data), farmers who did not use glyphosate for the studied agricultural cycle had variable yields, which were not statistically different from those who did use it (Supplementary Figures 7, 8). These results support Colbach et al. (2020) proposal, who suggest that reducing herbicide use rarely results in yield losses, especially if the farmers compensate with other management practices. In addition, it has been seen that the intensity of herbicide use has no direct relation to crop yield (Wies et al., 2022). Usually, this intensity depends on other management practices and their frequency, such as tillage and the mechanical control of weeds (Colbach and Cordeau, 2018). In our sample, the cases that did not use glyphosate and had considerable yields could represent alternatives put into practice, which are important to study in greater detail.

Regional socio-ecological heterogeneity and its relationship to glyphosate use

Given regional heterogeneity, particular characteristics affect glyphosate use in each region. This interregional and intraregional heterogeneity has been indicated as a determinant in maize production and management practices at the national level, in addition to being a challenge for policy interventions (Keleman et al., 2009; Eakin et al., 2015). For example, the family size and the use of large quantities of glyphosate in the AV region show us the interrelation of temporary migration, the productive age of the farmer, and the performance of other economic activities. These characteristics can be irrelevant in sites that can hire day workers, but in those with economic or workforce constraints, it can be a crucial determinant.

Another example is the combination of hybrid and *criollo* seeds in the VO region, which fulfill different needs in the farmers' livelihood. Usually, *criollo* maize production is destined for self-supply with less investment and inputs, including glyphosate; while hybrid maize is market-driven using more investment and inputs (Bellon and Hellin, 2011). Therefore, incentivizing the planting of *criollo* maize in some regions can help decrease glyphosate use, above all if *criollo* maize prices are competitive (Keleman et al., 2013). While other differences in management practices can be found between *criollo* and hybrid maize—like herbicide application timing (Bellon, 1991)—these were not explored here and represent a knowledge gap.

Another result that is worth discussing is how three of the four studied regions do not differ statistically in the volumes of glyphosate, 2,4-D, and paraquat used (Table 3). Unlike this tendency, in the MC region, various conditions, such as the possibility of mechanization, plots with river floodplain influence, crop rotations, and experimentation with greater planting densities (Wies et al., 2022), significantly reduce glyphosate use. It has been shown that increasing the planting density of maize by more than twice the recommended density can reduce weed biomass by up to 99% (Mhlanga et al., 2016). All these characteristics make farmers in this region less dependent on glyphosate and, in turn, less susceptible to its elimination. It would then be more compelling to look for alternatives to the use of glyphosate in regions that do not have these characteristics.

Conclusions

This study identifies a series of social, biophysical, and management variables that lead to syndromes from high or low glyphosate use by smallholder farmers in different regions of Chiapas. Greater use of glyphosate is usually accompanied by greater use of other herbicides, such as 2,4-D and paraquat. Small production units (<0.67 ha), high altitudes in mountainous areas, indigenous population, and rainfed conditions are characteristics associated with greater glyphosate use. In three of the four studied regions, the volumes of glyphosate used are very similar to the range reported for industrial agriculture. In exploring glyphosate use by region, other significant variables emerge at the local level, such as the smallholder's age, size of the nuclear family, or type of seed sown (*criollo* or hybrid). This study shows how the smallholder production sector—vital in providing maize on a national scale—is strategic for transitioning to the disuse of glyphosate.

Since this study worked with few farmers in a particular region, it has shortcomings in generalizing to the maize farming sector, other studies in different regions and socio-ecological conditions should be conducted to create a nuanced transition policy. Although, in Chiapas, as in many other Mexican states, for various decades the use of agrochemicals, including glyphosate, has been promoted and incentivized through diverse governmental programs partnering with national and international agribusiness companies. This is why, we consider it crucial to strengthen the autonomy of smallholders and their livelihoods with less dependence on external inputs and, above all, inputs that endanger human health and ecosystems. These recommendations support the idea that a change of the current production model is necessary, focusing on having more sustainable agricultural systems and not a substitution of one input for another. Many agroecological alternatives for weed management already exist, and it will be very important to mobilize them in the transition process.

Data availability statement

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

Author contributions

AM-S and MA contributed to conception and design of the study. LG-B gave conceptual insights for developing sections. AM-S, GW, RP, and DM-dL wrote sections of the manuscript and organized the dataset. AM-S and GW performed statistical analysis. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare 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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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.908779/full#supplementary-material

References

Adeux, G., Munier-Jolain, N., Meunier, D., Farcy, P., Carlesi, S., Barberi, P., et al. (2019). Diversified grain-based cropping systems provide long-term weed control while limiting herbicide use and yield losses. *Agron. Sustain. Dev.* 39, 42. doi: 10.1007/s13593-019-0587-x

Alcántara-de la Cruz, R., Cruz-Hipolito, H. E., Domínguez-Valenzuela, J. A., and De Prado, R. (2021). Glyphosate ban in Mexico: potential impacts on agriculture and weed management. *Pest Manag. Sci.* 77, 3820–3831. doi: 10.1002/ps.6362

Anaya-Zamora, C., Mier y Terán, M., Urdapilleta-Carrasco, J., and Ferguson, B. G. (2020). Retos y estrategias para la reducción del uso de plaguicidas en Chiapas, México, desde la perspectiva de las organizaciones de la sociedad civil. *Agric. Soc. Desarro.* 17, 91–119. doi: 10.22231/asyd.v17i1.1324

Arellano-Aguilar, O., and Rendón von Osten, J. (2016). *La Huella de Los Plaguicidas en México*. Ciudad de México: Greenpeace México.

Arellano-Monterrosas, J. L., Camacho-Álvarez, D. A., García, A. C., García-Castillo, M., Muñoz-Cervantes, E. G., Ruíz-Meza, L. E., et al. (2002). *Diagnóstico Regional de la Cuenca del río El Tablón en la Reserva de la Biosfera de La Sepultura, Chiapas*. San Cristóbal de las Casas: Universidad Autónoma Chapingo.

Beckie, H. J. (2011). Herbicide-resistant weed management: focus on glyphosate. *Pest Manag. Sci.* 67, 1037–1048. doi: 10.1002/ps.2195

Beckie, H. J., Flower, K. C., and Ashworth, M. B. (2020). Farming without glyphosate? *Plants* 9, 96. doi: 10.3390/plants9010096

Bellon, M. R. (1991). The ethnoecology of maize variety management: a case study from Mexico. *Hum. Ecol.* 19, 389–418. doi: 10.1007/BF00888984

Bellon, M. R., Adato, M., Becerril, J., and Mindek, D. (2006). Poor farmers' perceived benefits from different types of maize germplasm: The case of creolization in lowland tropical Mexico. *World Dev.* 34, 113–129. doi: 10.1016/j.worlddev.2005.05.012

Bellon, M. R., and Hellin, J. (2011). Planting hybrids, keeping landraces: agricultural modernization and tradition among small-scale maize farmers in Chiapas, Mexico. *World Dev.* 39, 1434–1443. doi: 10.1016/j.worlddev.2010.12.010

Bellon, M. R., Mastretta-Yanes, A., Ponce-Mendoza, A., Ortiz-Santamaria, D., Oliveros-Galindo, O., Perales, H., et al. (2018). Evolutionary and food supply implications of ongoing maize domestication by Mexican campesinos. *Proc. R. Soc. B Biol. Sci.* 285, 20181049. doi: 10.1098/rspb.2018.1049

Benbrook, C. M. (2016). Trends in glyphosate herbicide use in the United States and globally. *Environ. Sci. Eur.* 28, 1–15. doi: 10.1186/s12302-016-0070-0

Bernardino, H. (2013). *Plaguicidas: percepciones de su uso en comunidades rurales de Los Altos de Chiapas*. (Dissertation), El Colegio de la Frontera Sur, San Cristóbal de las Casas (Mexico).

Bernardino, H., Mariaca, R., Nazar, A., Álvarez, J., Torres, A., and Herrera, C. (2016). Factores socioeconómicos y tecnológicos en el uso de agroquímicos en tres sistemas agrícolas en los altos de Chiapas, México. *Interciencia* 41, 382–392.

Borcard, D., Gillet, F., and Legendre, P. (2011). *Numerical Ecology With R*. New York, NY: Springer. doi: 10.1007/978-1-4419-7976-6

Borggaard, O. K., and Gimsing, A. L. (2008). Fate of glyphosate in soil and the possibility of leaching to ground and surface waters: a review. *Pest Manag. Sci.* 64, 441–456. doi: 10.1002/ps.1512

Brush, S. B., and Perales, H. R. (2007). A maize landscape: Ethnicity and agro-biodiversity in Chiapas Mexico. *Agric. Ecosyst. Environ.* 121, 211–221. doi: 10.1016/j.agee.2006.12.018

Carey, B. W., Stone, B., Norman, P. L., and Shilton, P. (2015). "Land management on flood plains," in *Soil Conservation Guidelines for Queensland* (Queensland: Queensland Government), 1–41. Available online at: https://www.publications.qld.gov.au/dataset/soil-conservation-guidelines

Chikoye, D., Schulz, S., and Ekeleme, F. (2004). Evaluation of integrated weed management practices for maize in the northern Guinea savanna of Nigeria. *Crop Prot.* 23, 895–900. doi: 10.1016/j.cropro.2004.01.013

Clapp, J. (2021). Explaining growing glyphosate use: the political economy of herbicide-dependent agriculture. *Glob. Environ. Chang.* 67, 102239. doi: 10.1016/j.gloenvcha.2021.102239

Colbach, N., and Cordeau, S. (2018). Reduced herbicide use does not increase crop yield loss if it is compensated by alternative preventive and curative measures. *Eur. J. Agron.* 94, 67–78. doi: 10.1016/j.eja.2017.12.008

Colbach, N., Petit, S., Chauvel, B., Deytieux, V., Lechenet, M., Munier-Jolain, N., et al. (2020). The pitfalls of relating weeds, herbicide use, and crop yield: don't fall into the trap! a critical review. *Front. Agron.* 2, 615470. doi: 10.3389/fagro.2020.615470

CONACYT (2020). *Expediente Científico Sobre el Glifosato y Los Cultivos GM*. Ciudad de México: Consejo Nacional de Ciencia y Tecnología, Gobierno de México.

CONEVAL (2020). *Estadísticas de Pobreza en Chiapas. Medición de Pobreza 2020.* CONEVAL. Available online at: https://www.coneval.org.mx (accessed March 2, 2022).

Cortina-Villar, S., Plascencia-Vargas, H., Vaca, R., Schroth, G., Zepeda, Y., Soto-Pinto, L., et al. (2012). Resolving the conflict between ecosystem protection and land use in protected areas of the Sierra Madre de Chiapas, Mexico. *Environ. Manage.* 49, 649–662. doi: 10.1007/s00267-011-9799-9

Desquilbet, M., Bullock, D. S., and D'Arcangelo, F. M. (2019). A discussion of the market and policy failures associated with the adoption of herbicide-tolerant crops. *Int. J. Agric. Sustain.* 17, 326–337. doi: 10.1080/14735903.2019.1655191

DOF (2020). *Decreto Para Sustituir Gradualmente El Uso, Adquisición, Distribución, Promocioón E Inportación De La Sustancia Química Denominada Glifosato [...]*. Ciudad de México: Diario Oficial de la Federación, Estados Unidos Mexicanos.

Eakin, H., Appendini, K., Sweeney, S., and Perales, H. (2015). Correlates of maize land and livelihood change among maize farming households in Mexico. *World Dev.* 70, 78–91. doi: 10.1016/j.worlddev.2014.12.012

Eakin, H., Perales, H., Appendini, K., and Sweeney, S. (2014). Selling maize in Mexico: the persistence of peasant farming in an era of global markets. *Dev. Change* 45, 133–155. doi: 10.1111/dech.12074

Food and Agriculture Organization (2018). *The 10 Elements of Agroecology Guiding the Transition to Sustainable Food and Agricultural Systems.* Food and Agriculture Organization. Available online at: http://www.fao.org/3/I9037EN/i9037en.pdf (accessed January 20, 2022).

García-Barrios, L., Galván-Miyoshi, Y. M., Valdivieso-Pérez, I. A., Masera, O. R., Bocco, G., and Vandermeer, J. (2009). Neotropical forest conservation, agricultural intensification, and rural out-migration: The Mexican experience. *Bioscience* 59, 863–873. doi: 10.1525/bio.2009.59.10.8

González-Ortega, E., Piñeyro-Nelson, A., Gómez-Hernández, E., Monterrubio-Vázquez, E., Arleo, M., Dávila-Velderrain, J., et al. (2017). Pervasive presence of transgenes and glyphosate in maize-derived food in Mexico. *Agroecol. Sustain. Food Syst.* 41, 1146–1161. doi: 10.1080/21683565.2017.1372841

Hunt, N. D., Hill, J. D., and Liebman, M. (2017). Reducing freshwater toxicity while maintaining weed control, profits, and productivity: effects of increased crop rotation diversity and reduced herbicide usage. *Environ. Sci. Technol.* 51, 1707–1717. doi: 10.1021/acs.est.6b04086

INEGI (2019). *Encuesta Nacional Agropecuaria*. INEGI. Available online at: https://www.inegi.org.mx/programas/ena/2019/ (accessed November 8, 2021).

Instituto Nacional de Ecología y Cambio Climático., Martinez, A., Ruiz, L., Gavilán, A., and Mendoza, A. (2020). *Perspectivas de las Importaciones y Exportaciones de Plaguicidas en México.* Ciudad de México: Instituto Nacional de Ecología y Cambio Climático.

International Agency for Research on Cancer (2017). *Some Organophosphate Insecticides and Herbicides: IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*. Lyon: World Health Organization.

Keleman, A., Hellin, J., and Bellon, M. R. (2009). Maize diversity, rural development policy, and farmers' practices: lessons from Chiapas, Mexico. *Geogr. J.* 175, 52–70. doi: 10.1111/j.1475-4959.2008.00314.x

Keleman, A., Hellin, J., and Flores, D. (2013). Diverse varieties and diverse markets: scale-related maize "profitability crossover" in the central mexican highlands. *Hum. Ecol.* 41, 683–705. doi: 10.1007/s10745-013-9566-z

Li, J., Han, H., Bai, L., and Yu, Q. (2020). 2,4-D antagonizes glyphosate in glyphosate-resistant barnyard grass Echinochloa colona. *J. Pestic. Sci.* 45, 109–113. doi: 10.1584/jpestics.D20-013

Liebman, M., Mohler, C. L., and Staver, C. P. (2004). *Ecological Management of Agricultural Weeds*, eds M. Liebman, C. L. Mohler, and C. P. Staver Cambridge (Cambridge: Cambridge University Press).

MacLaren, C., Storkey, J., Menegat, A., Metcalfe, H., and Dehnen-Schmutz, K. (2020). An ecological future for weed science to sustain crop production and the environment. A review. *Agron. Sustain. Dev.* 40, 24. doi: 10.1007/s13593-020-00631-6

Maldonado-López, L. G., Mariaca-Méndez, R., Nazar-Beutelspacher, A., Rosset, P., and Contreras-Cortés, U. (2017). Mujeres: barro y maíz. Mujeres rurales y estrategias de subsistencia en Amatenango del Valle, Chiapas. *Rev. Geogr. Agrícola* 59, 55–85. doi: 10.5154/r.rga.2017.59.001

Malkanthi, S. H. P., Sandareka, U. G., Wijerathne, A. W., and Sivashankar, P. (2019). Banning of glyphosate and its impact on paddy cultivation: a study in Ratnapura district in Sri Lanka. *J. Agric. Sci.* 14, 129–144. doi: 10.4038/jas.v14i2.8515

Mariaca-Méndez, R., Pérez-Pérez, J., López-Meza, A., and León-Martínez, N. S. (2007). *La Milpa Tsotsil De Los Altos de Chiapas y Sus Recursos Genéticos*. San Cristóbal de las Casas: El Colegio de la Frontera Sur, Universidad Intercultural de Chiapas.

Mascorro-de Loera, R. D., Ferguson, B. G., and Perales-rivera, H. R. (2019). Herbicidas en la milpa: estrategias de aplicación y su impacto sobre el consumo de arvenses. *Ecosistemas Recur. Agropecu.* 6, 477–486. doi: 10.19136/era.a6n18.2076

McClung de Tapia, E., Martínez Yrízar, D., Ibarra Morales, E., and Adriano Morán, C. C. (2014). Los orígenes prehispánicos de una tradición alimentaria en la cuenca de México. *An. Antropol.* 48, 97–121. doi: 10.1016/S0185-1225(14)70491-6

Mhlanga, B., Chauhan, B. S., and Thierfelder, C. (2016). Weed management in maize using crop competition: a review. *Crop Prot.* 88, 28–36. doi: 10.1016/j.cropro.2016.05.008

Pacheco-Ladrón de Guevara, L. C. (1999). *Nomás Venimos a Mal Comer. Jornaleros Indios en el Tabaco en Nayarit. Dirección de Investigación Científica Tepic.* Nayarit: Universidad Autónoma de Nayarit.

PAN (2018). *Alternatives Methods in Weed Management to the Use of Glyphosate and Other Herbicides, 2nd edn*. Brussels: Pesticide Action Network.

Parsons, D., Ramírez-Aviles, L., Cherney, J. H., Ketterings, Q. M., Blake, R. W., and Nicholson, C. F. (2009). Managing maize production in shifting cultivation milpa systems in Yucatán, through weed control and manure application. *Agric. Ecosyst. Environ.* 133, 123–134. doi: 10.1016/j.agee.2009.05.011

Pavesi, R. (2018). *Valutazione della sostenibilità di sistemi agroforestali in Chiapas, Messico: necessità di sviluppare approcci al di là dello sviluppo sostenibile*. (Master's thesis), Study University of Milan, Milan (Italy).

Perales, H., and Golicher, D. (2014). Mapping the diversity of maize races in Mexico. *PLoS ONE* 9, e0114657. doi: 10.1371/journal.pone.0114657

Puyana, A. (2012). Mexican agriculture and NAFTA: a 20-year balance sheet. *Rev. Agrar. Stud.* 2, 1–43.

R Core Team (2019). *R: A Language and Environment for Statistical Computing*. Viena: R Foundation for Statistical Computing.

Ramírez Muñoz, F. (2021). *El herbicida Glifosato y Sus Alternativas*. San José, CA: Universidad Nacional de Costa Rica.

Richards, B. K., Pacenka, S., Meyer, M. T., Dietze, J. E., Schatz, A. L., Teuffer, K., et al. (2018). Antecedent and post-application rain events trigger glyphosate transport from runoff-prone soils. *Environ. Sci. Technol. Lett.* 5, 249–254. doi: 10.1021/acs.estlett.8b00085

Rosenzweig, S. T., Stromberger, M. E., and Schipanski, M. E. (2018). Intensified dryland crop rotations support greater grain production with fewer inputs. *Agric. Ecosyst. Environ.* 264, 63–72. doi: 10.1016/j.agee.2018.05.017

Storkey, J., and Neve, P. (2018). What good is weed diversity? *Weed Res.* 58, 239–243. doi: 10.1111/wre.12310

Sweeney, S., Steigerwald, D. G., Davenport, F., and Eakin, H. (2013). Mexican maize production: evolving organizational and spatial structures since 1980. *Appl. Geogr.* 39, 78–92. doi: 10.1016/j.apgeog.2012.12.005

Todorovic, G. R., Rampazzo, N., Mentler, A., Blum, W. E. H., Eder, A., and Strauss, P. (2014). Influence of soil tillage and erosion on the dispersion of glyphosate and aminomethylphosphonic acid in agricultural soils. *Int. Agrophys.* 28, 93–100. doi: 10.2478/intag-2013-0031

Toledo, V. M. V. M., Ortiz-Espejel, B., Cortés, L., Moguel, P., and Ordoñez, M. J. (2003). The multiple use of tropical forests by indigenous peoples in Mexico: a case of adaptive management. *Conserv. Ecol.* 7, 9. doi: 10.5751/ES-00524-070309

Vázquez, V., Godínez, L., Montes Estrada, M., Montes, M., and Ortiz, A. S. (2004). Los quelites de Ixhuapan, Veracruz: disponibilidad, abastecimiento y consumo. *Agrociencia* 38, 445–455.

Vigouroux, Y., Barnaud, A., Scarcelli, N., and Thuillet, A.-C. (2011). Biodiversity, evolution and adaptation of cultivated crops. *C. R. Biol.* 334, 450–457. doi: 10.1016/j.crvi.2011.03.003

Wezel, A., Herren, B. G., Kerr, R. B., Barrios, E., Gonçalves, A. L. R., and Sinclair, F. (2020). Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. *Agron. Sustain. Dev.* 40, 40. doi: 10.1007/s13593-020-00646-z

Wies, G., Navarrete-Segueda, A., Ceccon, E., Larsen, J., and Martinez-Ramos, M. (2022). What drives management decisions and grain yield variability in Mesoamerican maize cropping systems? Evidence from small-scale farmers in southern Mexico. *Agric. Syst.* 198, 103370. doi: 10.1016/j.agsy.2022.103370

Yin, K. R. (2003). *Case Study Research: Design and Methods, 3rd Edn*. Thousand Oaks, CA: Sage Publications.

Zermeño-Hernández, I., Pingarroni, A., and Martínez-Ramos, M. (2016). Agricultural land-use diversity and forest regeneration potential in human-modified tropical landscapes. *Agric. Ecosyst. Environ.* 230, 210–220. doi: 10.1016/j.agee.2016.06.007

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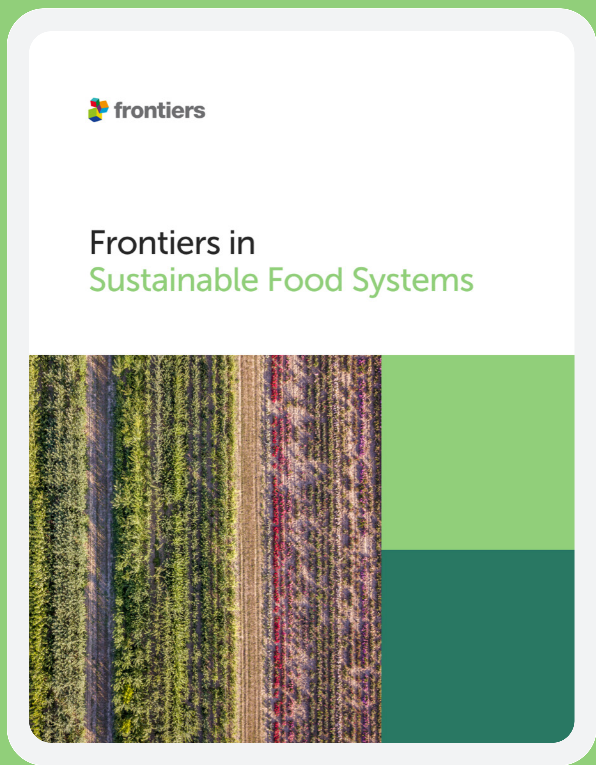

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