FOOD SECURITY, AGRICULTURAL PRODUCTIVITY, AND THE ENVIRONMENT: ECONOMIC, SUSTAINABILITY, AND POLICY PERSPECTIVES

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Editorial: Food Security, Agricultural Productivity, and the Environment: Economic, Sustainability, and Policy Perspectives

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Keywords: Sustainable Development goals, food systems, climate change, institutions, ecosystem services

Editorial on the Research Topic

Food Security, Agricultural Productivity, and the Environment: Economic, Sustainability, and Policy Perspectives

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As we move forward to meet the challenge of feeding 9.6 billion people by 2050, trade-offs between agricultural productivity and environmental conservation are going to intensify. Nearly 9% of the world's population is undernourished (Roser and Ritchie 2019), largely in the developing parts of the world where agricultural systems are characterized by smallholders and weak institutional structures. Increasing food demands are thereby met with either intensive efforts to increase yields or to expand agricultural crop land. On the other hand, agricultural yields are projected to decrease in the next decades in most world regions due to climate change impacts such as droughts, soil desertification, floods, sea level rise and soil salinization that might also interact with an increased frequency of diseases and pathogens in crop, and livestock production (Ringsmuth et al., 2022). We can also expect that the competition for land use will intensify due to the low-carbon transition that must be achieved by mid-century. Getting away from fossil-fuels and expanding renewables will require massive amounts of the Earth's surface (Otto et al., 2020). Some compromises with land use for food production and consumption, as well as land use of human settlements and infrastructure will have to be found.

Efforts towards increasing agricultural productivity to solve some of these problems can have a direct impact on the natural resource base such as soil and water. At the same time, geopolitical crises intensify disruptions of global supply chains and food shortages. It is increasingly clear that the war in Ukraine that started 1 month ago will negatively impact the global supply of grains. Many countries that relied in the past on grain imports from Ukraine are located in Northern Africa, have a high share of population exposed to poverty and hunger, and many of them are politically unstable (Knaepen and Dekeyser 2022). In addition, induced by the war in Ukraine, high fossil fuel energy prices may soon lead to higher prices for agricultural inputs, which in consequence could lead to higher food prices.

In this Research Topic, we present ten articles that address a deeper understanding of the inter-linkages and potential solutions for achieving pathways to meet increasing food demand through improved agricultural processes that can co-exist with environmental conservation objectives, especially as envisaged under the Sustainable Development Goals (SDGs). Contributions come from various fields and include analyses of trade-offs between food security, agricultural productivity and environmental goals, spanning various geographical scales, and analytical foci. While grouping the diverse contributions is not an easy task, it is analytically useful to provide a broader perspective on these contributions.

Three articles provide new frameworks and meta-perspectives on rethinking food systems, acknowledging the increasing importance of low probability, but high-impact events such as the SARS-CoV-2 pandemic, the Ukraine war, or climate change. While it is difficult to fully capture the complexity of food systems and the many unpredictable cascading effects major crises trigger in these systems, Hogeboom et al., Manevska-Tasevska et al., as well as Srigiri and Dombrovsky adopt novel perspectives which assess food systems in their response to shocks. Focusing on attributes such as the modularity, diversity, or redundancy of a specific food system can provide novel insights that augment more narrowly focused disciplinary analysis. A second set of articles is concerned with the embeddedness of actors within organizations and institutions (understood as sets of rules). Providing an in-depth understanding of local cases, Ires; Yu and Nilsson; Censkowsky and Otto, as well as Xiao and You, critically discuss the complex interplay between heterogeneous actors and legal or organizational frameworks. Finally, three articles—Enriquez et al., Markandya et al., and Vittis et al. —synthesize current global evidence or provide long-term historic perspectives on food systems at national scales. For instance, Markandya et al. point out that building a better post-Covid future would require moving beyond immediate economic risk management and making substantial investments to promote food security, healthy diets, environmental sustainability, rural livelihoods, and social justice.

We believe that these contributions are essential for understanding challenges which global food production will face over the next months and years. The type of human-nature interactions in food production that have been developed in the second part of the 20th Century will have to undergo profound changes. An answer could be to adequately incentivize locally closed nutrient cycles which will also imply that consumers need to rely more on local ecosystem services, as discussed by Censkowsky and Otto. This would also be in line with a greater political emphasis placed on self-sufficiency in times of crises. Many studies also point towards novel regenerative types of agricultural systems or sustainable intensification practices that promise food production modes that may have lower or even net positive environmental and social impacts (Garnett et al., 2013; Newton et al., 2020). The contributions gathered under this Research Topic, help to understand which policies and constellations of stakeholders will be essential to guide the transformation that we are currently facing.

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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REVIEW
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Resilience Meets the Water–Energy–Food Nexus: Mapping the Research Landscape

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Resilience thinking is increasingly promoted to address some of the grand challenges of the 21st century: providing water, energy, and food to all, while staying within the limits of the Earth system that is undergoing (climate) change. Concurrently, a partially overlapping body of literature on the water–energy–food (WEF) nexus has emerged through the realization that water, energy, and food systems are intricately linked—and should therefore be understood and managed in conjunction. This paper reviews recent scientific publications at the intersection of both concepts in order to i) examine the status quo on resilience thinking as it is applied in WEF nexus studies; ii) map the research landscape along major research foci and conceptualizations; iii) and propose a research agenda of topics distilled from gaps in the current research landscape. We identify key conceptualizations of both resilience and nexus framings that are used across studies, as we observe pronounced differences regarding the nexus' nature, scope, emphasis and level of integration, and resilience's scope, type, methodological and thematic foci. Promising research avenues include i) improving the understanding of resilience in the WEF nexus across scales, sectors, domains, and disciplines; ii) developing tools and indicators to measure and assess resilience of WEF systems; iii) bridging the implementation gap brought about by (governing) complexity; iv) integrating or reconciling resilience and nexus thinking; v) and considering other development principles and frameworks toward solving WEF challenges beside and beyond resilience, including control, efficiency, sustainability, and equity.

Keywords: water–energy–food nexus, resilience, Sustainable Development Goals, water security, food security, energy security, transformation

INTRODUCTION

Major economic advancements in the 20th century have lifted millions out of poverty and provided water, energy and food to millions more (UNDP, 2016). However, it has become clear that these successes have come and continue to come at a cost to natural capital. In many regions, aquatic and terrestrial ecosystems have degraded beyond repair, resources have been depleted, species are becoming extinct at alarmingly high rates, and vulnerability to shocks has increased (Turner et al., 2003; Vörösmarty et al., 2010; Puma, 2019).

At the same time, millions of people have been left behind in the global development spur. Today still, three in ten people, i.e., 2.1 billion, are lacking access to safe drinking water and six in ten lack safely managed sanitation facilities (UN-WWAP, 2019); nearly one billion people remain deprived of electricity (OECD and IEA, 2018); more than 820 million people have insufficient food, and many more consume unhealthy diets that contribute to premature death and morbidity (Fears et al., 2019; Willett et al., 2019).

Both the negative environmental impacts and insecurity of water, energy and food supply are expected to worsen in the near future, driven by population growth, increasingly resource-intensive lifestyles and vulnerabilities to disruptive shocks including climate change (Hoekstra and Wiedmann, 2014; Steffen et al., 2018). Reaching the UN's Sustainable Development Goals (SDGs), including those on food (SDG 2), water (SDG 6) and energy (SDG 7), require substantial, if not transformative efforts across the actor landscape (FAO et al., 2017; United Nations, 2018; IRENA, 2019). Indeed, one of the major challenges in the Anthropocene epoch is to provide basic human necessities of water, energy and food to all, in an environmentally sustainable, economically viable and socially inclusive manner that is capable to cope with shocks and disasters (Sachs et al., 2019). These challenges call for new ways of thinking on how we manage natural resources (Pingali, 2012; Nyström et al., 2019).

One such contemporary paradigm is the 'nexus approach'. Originating in public debates on environmental policy, nexus thinking advocates that water, energy and food systems should be viewed collectively and holistically in order to reach water, energy and food (WEF) security (WEF, 2011; Bleischwitz et al., 2018; Liu et al., 2018). Nexus thinking emphasizes the need to consider interlinkages between WEF systems and integrate their management, in order to reduce trade-offs and build synergies across these key sectors, thus presenting a contrasting framework to traditional sectoral approaches (Al-Saidi and Elagib, 2017; Hoff et al., 2019).

Concurrently, 'resilience thinking' emerged in scientific debates (Holling, 1973). Evolving from the field of ecology, resilience thinking is strongly anchored in sustainability science and global change research (Folke et al., 2010; Scheffer et al., 2012; Anderies, 2015). In an uncertain and complex world, unforeseen shocks and disasters can proliferate across scales and systems in unexpected ways, reducing system performance (Nyström et al., 2019). Resilience thinking, therefore, emphasizes the need to design, develop and manage systems for resilience such that they can sustain their function when facing inevitable disturbances, be it sudden disturbances such as a pandemic or those of longer duration such as climate change (World Bank, 2013; Hall et al., 2014; UNDP, 2014; Grafton et al., 2019).

Both nexus and resilience framings find increasingly fertile ground in science as well as policy arenas, where each is backed and cultivated by a growing community of advocates. However, it remains unclear to what extent they are capable to deliver on their promise and materially contribute to WEF security goals. Both framings have been criticized for, among others, their epistemological agility, their conceptual dissonance (both within and across disciplines), and—perhaps as a consequence—their lack of practical merit toward solving major global challenges (Olsson et al., 2015; Cairns and Krzywoszynska, 2016; Folke, 2016; Gillard, 2016). While the general notion of resilience as 'the capacity of a system to cope with shocks' is widely shared, the specific conceptualizations of the shocks, tools, methods and approaches underlying it vary greatly across literature (Grafton et al., 2016; Allen et al., 2019). Likewise for the nexus, the plurality of typologies yields a spectrum that ranges from simply acknowledging that connections exist between water, food and energy systems, to proposing advanced analytical frameworks for integrated WEF policy development (Scott et al., 2011; Leck et al., 2015; Albrecht et al., 2018). At the same time, there is an occasional overlap in the aims and concepts in both framings, which led several scholars to attempt to integrate the two schools of thought (Guillaume et al., 2015; de Grenade et al., 2016; Stringer et al., 2018).

Given the growing prominence of both nexus and resilience framings in recent literature, as well as expressed concerns over their merit and conceptual clarity, we set out to review recent scientific publications that conflate the two schools of thought. Specifically, the aim of this paper is to:

i) examine the status quo of resilience thinking as it is applied in WEF nexus studies, by reviewing recent scientific publications at the intersection of both concepts;
ii) map the research landscape, by identifying key research foci and conceptualizations of nexus and resilience framings;
iii) propose a research agenda, by distilling recommendations and knowledge gaps from the reviewed publications.

The body of research on both resilience and nexus thinking is substantial and extends over various research domains. This paper does not attempt to resolve all semantic dissonances or fundamental critiques surrounding both framings, nor does it aspire to provide a full coverage of resilience and nexus literature. Rather, it tries to help those interested in (applying) resilience and WEF nexus thinking understand the state of affairs in this growing body of literature and identify future avenues of research.

METHODS

A quick key word search in major scientific databases reveals the vast body of literature on resilience, with over 100,000 hits across all disciplines, of which more than 22,000 are in disciplines relevant to sustainability science. The WEF nexus literature, in turn, boasts over 1,000 peer-reviewed publications. While we provide a short overview on both concepts in "**Characterizing the WEF Nexus**" and "**Characterizing Resilience**" sections reviewing all resilience and nexus studies that have a bearing on water, energy, and food is beyond our scope. For our formal review of scientific publications, we confined ourselves to those that explicitly conflate both domains. That is, we specifically examined the status quo on resilience thinking as it is applied in WEF nexus studies and selected only those scientific publications for review that explicitly make mention of both resilience and nexus concepts. The following criteria were used to define our pool of publications to be reviewed:

- The publication is included in the Web of Science or Scopus database;
- The publication is peer-reviewed (e.g., research articles, review papers, conference proceedings, books, and book chapters). Gray literature, although substantial, is excluded;
- The title, keywords or abstract of the publication include terms that relate to the WEF nexus, viz. "nexus" in combination with "water", "food" or "agricultur*", and "energy" or "electricity";
- The title, keywords or abstract of the publication include terms that relate to resilience thinking, viz. resilien*" or "transforma*";
- The publication is published between 2011 and 2020 (as the nexus was first coined in 2011 Hoff, 2011).

While this procedure, which was carried out in February 2020, results in a base set of publications, it may exclude other relevant ones. For example, adaptive capacity, robustness, and vulnerability are concepts often used in resilience thinking, but if not explicitly mentioned alongside resilience, these references are not captured in our search criteria. The same goes for bordering concepts from e.g., urban metabolism studies, sustainability science, systems thinking and political ecology (Dalla Fontana and Boas, 2019). Furthermore, because of this paper's focus on water, energy and food, publications that include other nexus facets, such as climate (Chirisa and Bandauko, 2015), soil (Hatfield et al., 2017), health (Mabhaudhi et al., 2016), and trade (Pastor et al., 2019), are not necessarily captured by the search. To at least partly overcome these shortcomings, the authors—who have a background in either a WEF domain or resilience discourse—cross-checked the list and supplemented where necessary from their own expertise. Hence, while we do not hold to the illusion that we are complete in reviewing all there is to say about resilience and the WEF nexus, we believe have included a substantial and representative proportion of the scientific literature.

The dataset thus obtained contained 166 publications. After an initial round of review, several publications were found to merely refer to resilience or the nexus in passing or as a general (buzz) word, rather than to the approach or the school of thought that these terms represent. Such publications were excluded from further scrutiny, so that the definitive set of publications that forms the basis for mapping the research landscape constitutes 43 documents (**Supplementary Material** provides an overview).

Given the conceptual dissonance around both approaches, we hypothesized that the research landscape would be highly divergent and heterogeneous. We therefore characterized the research landscape in order to structure our mapping exercise and provide clarity. Hereto, several key dimensions or conceptualizations of both resilience and nexus concepts were distilled from a generic literature review on both schools of thought (see "**Characterizing the WEF Nexus**", "**Characterizing Resilience**", "**Spatial Scale and Case Study**" sections). Next, we developed a spreadsheet for data analysis to classify and map the selected publications accordingly (section "**Mapping the Research Landscape**").

The analysis of the results of the mapping exercise led to a preliminary research agenda. Complemented by recommendations for further research mentioned in the reviewed publications themselves, we synthesized these findings and converged the long list of potential research avenues into five broad categories of further research opportunities.

RESILIENCE AND THE WEF NEXUS

Both resilience and nexus framings have a long pedigree and an active backing from scholarly communities. According to Al-Saidi and Elagib (2017), nexus thinking finds its origins in environmental policy studies and public debate on natural resources management, while resilience has precursors in science debates on sustainability and systems thinking. Nexus thinking was first conceived at the WEF (2011), and most authors identify the flagship publication by Holling (1973) as the onset of resilience thinking insofar it became relevant in a WEF nexus context. Where the essence of the nexus is the about interconnections between water, energy and food systems, resilience is about the capacity of a system to respond to threats and retain its ability to deliver benefits (Lawford et al., 2013; Grafton et al., 2016). Given the many excellent expositions that have been written on each concept already, we will refrain from repeating their findings here, and instead refer the reader to comprehensive and recent reviews on either the nexus by Ringler et al. (2013); Al-Saidi and Elagib (2017); Albrecht et al. (2018); Liu et al. (2018); Bleischwitz et al. (2018) or on resilience by Carpenter et al. (2001); Walker et al. (2006); Hollnagel et al. (2006); Folke et al. (2010); Béné and Doyen (2018); Moser et al. (2019). The next sections, rather, expound on distilling general characteristics that are shared or accepted within different (sub)fields or arenas of nexus and resilience research, respectively. They are summarized in **Table 1**.

Characterizing the WEF Nexus

Scope of the Nexus

The first major dichotomy in nexus literature pertains to the interpretation, or scope, of the term nexus itself. The nexus can either be perceived (i.e., scoped) as a descriptive account of interactions and interdependencies between different natural resources *systems*; or it can be scoped as an *approach* that enables and supports transition across sectors and stakeholders in these systems (Howells et al., 2013; Howarth and Monasterolo, 2016).

The notion of the nexus as linked *systems* is found in Bleischwitz et al. (2018) and Dalla Fontana and Boas (2019), for example, who present the nexus as a term referring to context-

TABLE 1 | Characteristics of the WEF nexus and resilience literature, which are used to map the research landscape.

Concept	Dimension	Operationalisation
Nexus	Scope of the nexus	Approach, system
	Emphasis on nexus components	Water, energy, food, equal WEF
	Level of nexus integration	Incorporation, cross-linking, assimilation
Resilience	Scope of resilience	Engineering resilience (ER), social-ecological systems (SES) resilience, transformation
	Type of resilience	Specified, general
	Methodological focus	Theorizing, building, measuring, modeling
	Thematic domain	Infrastructure, policy, governance, social capital, investment, technology
	Disturbance source	Internal, external
	Disturbance phase	Foresee, cope, recover
Both	Spatial scale	Local, national, regional, global
	Case study	Yes, No

specific interlinkages between different natural resource systems, including water, energy and food. Stringer et al. (2018) elaborate this perspective as follows: "To explain the nexus in its simplest form, water is needed to generate energy, energy is needed to supply water, energy is needed to produce food, food can be used to produce energy, water is needed to grow food, while food transports (virtual) water, often using energy". Note that we use the term *systems* to cover several more specific interpretations, such as the resources themselves, resource sectors, systems, or securities of resources. While we attempted to define the nexus scope at this higher level of granularity, we found that many studies fail to expound on their system interpretation or have ambiguous interpretations. In our scoring procedure, reviewed studies that scope the nexus as a *system* are thus taken to reflect all these underlying interpretations.

The notion of the nexus as an *approach*, in contrast, postulates that the nexus "identifies tradeoffs and synergies of water, energy and foods systems, internalizes social and environmental impacts, and guides development of cross-sectoral policies" (Albrecht et al., 2018). This nexus-as-approach notion is advocated as an advancement over current and often sector-specific governance of natural resources bridging the sectoral divides, or siloes, in mainly environmental policy integration (Hoff et al., 2019). Scoping the nexus as an approach thus not only acknowledges interlinkages that exist between WEF systems, but also includes systems thinking, considers different scales for problem solving, embraces complexity, and promotes participation in management and governance. It is this latter scoping that gave rise to the nexus as a frame for sustainability science, more than the former.

Emphasis on Nexus Components

While the WEF (2011) presented the nexus as an integrative framework for achieving WEF security, studies tend to emphasize either water, energy or food within the broader WEF nexus. For example, the early study by Hoff (2011) revolved mainly around water security, Villamor et al. (2020) emphasize the role of the energy system within the WEF nexus, and Ringler et al. (2013) food (as a resource and sector). Since nexus thinking has emerged from the water domain, it is often presented as a logical evolution from water-centric Integrated Water Resources Management (Allouche et al., 2015; Allouche, 2016). We therefore hypothesize that the water component is particularly emphasized in the WEF nexus research landscape, despite its intended integrative scope (cf. Benson et al., 2015; de Loe and Patterson, 2017). Note that in studies that scope the nexus as linked systems, nexus components may refer to inputs (water, energy, or food resources as input to achieve some other goal), as output (e.g., WEF security) or both. Since this focus is often implicit or ambiguous, reviewed studies that emphasize nexus components are taken to reflect any of these foci in our scoring procedure.

Level of Nexus Integration

A third nexus dimension identified in literature is the level at which components of the WEF nexus are integrated. While nexus studies often mention the importance of integrating water, energy and food systems, there is no consensus on what integration means. Al-Saidi and Elagib (2017) distinguish three levels of integration: *incorporation* is the most holistic view on the nexus that tries to describe and quantify as many interactions between the three resources as possible. Since incorporation implies an equal importance of the water, energy, and food concerns in the nexus, it is expected to be found in macro-level studies (e.g., high-level policy formulation, resource allocation and strategic investments). *Cross-linking* focuses on capturing specific interlinkages, mostly between two nexus components faced with major or priority issues. Examples include trade-off analyses between food and energy issues. Finally, *assimilation* implies looking at the nexus from the perspective of one specific sector while considering the links to other sectors. Assimilation tends to purport the view of sectoral or operational managers attempting to include other WEF components' concerns in their strategies.

Another way to understand the level of integration is presented by Gragg et al. (2018), where WEF systems are either unconnected or siloed; interconnected or linked; or interdependent and nested. The interconnected and interdependent systems categories seem to overlap with the cross-linking and incorporation levels postulated by Al-Saidi and Elagib (2017), respectively.

Characterizing Resilience

Key characteristics of resilience framings distilled from literature include its scope, type, methodological focus, thematic domain, and the source and phase of perceived disturbances.

Scope of Resilience

More than on the nexus, resilience literature sketches an image of a magic word with a wide spectrum of interpretations and diverse formulations across disciplines (Moser et al., 2019). While this conceptual dissonance allows for multiple valid characterizations, the first major dimension we identify here is the differentiation in scoping resilience.

Early resilience literature often uses the metaphor of a stability landscape, where resilience is a measure of the persistence of a system and of its ability to absorb change and disturbance while it remain in its basin of attraction (Holling, 1973). Cumulative disturbances may at some point move the system over a threshold of the current basin of attraction, thus bringing it into another, possibly undesirable domain (Gunderson and Holling, 2002). Resilience of the system, then, depends on the maximum amount of change tolerable within the basin of attraction (known as latitude), the ease of changing (resistance), the closeness of system thresholds (precariousness), and cross-scale interactions (panarchy) (Walker et al., 2004). While resilience encompasses the whole stability landscape, different fields emphasized different stability aspects. Specifically, when the behavior of the system in the neighborhood of an attractor within a given domain of attraction is of interest, resilience is understood as engineering resilience; when changes in the state of the system between different domains of attraction, but within the stability landscape of the system are of interest, we speak of social-ecological systems (SES) resilience; and when changes of the stability landscape are of interest, resilience is scoped as transformation (Gallopín, 2006).

Engineering resilience focusses on the speed of return to an equilibrium state after a disturbance, maintaining efficiency in the face of change, and resisting shocks to conserve system functioning (Holling, 1996; Walker et al., 2004; Folke, 2006). It is the most practical scoping of resilience that, as the name implies, is prevalent in the engineering sciences. Note that engineering resilience, while easily confused, is not the same as resilience engineering. Resilience engineering is a related concept that refers to a specific sub-field of safety research on failures in complex (engineered) systems, and aims to maintain system functioning while preventing harm to persons (Hollnagel et al., 2006; Righi et al., 2015; Provan et al., 2020).

SES resilience evolved more comprehensively as engineering resilience, focusing on a system's persistence, resistance, recovery and robustness, and acknowledging that multiple equilibria or stability landscapes exist (Grafton et al., 2019). It also underscores the importance of developing or maintaining adaptive capacity, learning and innovation potential in a system, in the context of integrated system feedbacks and cross-scale dynamic interactions (Walker et al., 2002; Anderies et al., 2004; Walker et al., 2004). In their citation network analysis, Baggio et al. (2015) found that SES resilience has become an important bridging concept in the interdisciplinary field of SES science.

Resilience as transformation can be viewed as an extreme yet distinct form of SES resilience. A resilient SES operates within a stable landscape where it can cope with minor disturbances. However, if shocks are too severe, a boundary is crossed (viz. a tipping point reached), resulting in a sudden or gradual transformation of the system into another stability landscape (Rockström et al., 2009; Guillaume et al., 2015). Transformation may imply dealing with risks of unwanted landscape change, but a good share of literature focusses on preparing for opportunity or creating conditions of opportunity for navigating the transformation as well (Scheffer et al., 2012; Béné and Doyen, 2018). Transformations typically take place over longer timescales of decades to centuries (Anderies et al., 2013).

Clearly, there are alternative characterizations to the three-fold scoping of resilience presented here. One such alternative with a strong analogy to the above is by Béné and Doyen (2018), who characterized resilience along a continuum of five degrees of changes allowed to the dynamics of the system at hand. The continuum starts with resilience as resistance, aimed at stability and avoiding system change; coping, aimed at absorption and buffering; adaptation, aimed at flexibility; adaptive preference, aimed at adjustment and changing expectations; and finally, transformation, aimed at changing the structure of the system.

Type of Resilience

The second characterization of resilience is—for the lack of a better term—the type of resilience. Authors may either deal with specified or general resilience. As particularly SESs can become extremely complex, a logical question arises: resilience of what to what? When the answer to this question is clear, this is referred to as specified resilience: it relates to a particular part of a system, a particular control variable within the system, and/or one or more identified kinds of shocks (Carpenter et al., 2001; Folke et al., 2010). Specified resilience therefore requires a careful definition of the system boundaries (Anderies et al., 2013).

In contrast, general resilience refers to any and all parts of a system to all kinds of shocks including novel ones (Folke et al., 2010). It focusses on broader system-level attributes such as the ability to build and increase the capacity for learning and adaptation (Walker et al., 2006). General resilience thus evaluates the effect of factors that affect resilience in SESs, such as (but not limited to) the presence of reserves, redundancies, diversity (of WEF sources), connectivity and modularity of trade networks, social capital, and adaptive governance structures (D'Odorico et al., 2018). By implication, general resilience studies are typically less careful about system definitions, nor about what resilience entails in practice (Anderies et al., 2013).

Methodological Focus

The next differentiating dimension we observe in resilience literature relates to the methodological focus of the research. We distinguish between studies which primarily focus on theorizing, building, measuring, or modeling resilience. The first focus, labeled theorizing, strives mainly to further the conceptual or theoretical understanding or underpinning of resilience, often perceiving resilience as an emergent system trait. Studies that focus on building resilience, in contrast, are primarily concerned with how to develop or design resilient systems. They often have a normative stance toward resilience, and adopt a management or governance perspective (cf Quinlan et al., 2016; Sellberg et al., 2018). Measuring and modeling studies are more technical in nature and self-explanatory. These four categories are not necessarily mutually exclusive and may overlap. For our review of the pool of publications (**Mapping the Research Landscape**) we tried to select the dominant methodological focus of each publication.

Thematic Domain

Many potential categories exist to describe thematic domains. Quinlan et al. (2016), for example distinguishes between studies focusing on the resilience of a system (e.g., a WEF system) vs. on the resilience of the governance of the system. Pahl-Wostl (2009) splits out resilience governance and management, where the former refers to the social and political process of defining goals for the management of a system, and management as the practical actions taken to achieve these goals. Biggs et al. (2012) address the importance of studying the role of institutions (focusing on building knowledge, incentives, and learning capabilities into institutions and organizations, (cf Folke (2006)), policy, and social capital (including educating and building skills in people, cf Nelson et al. (2007).

We identify infrastructure, (operational) policies, governance (including stakeholder and institutional considerations), social capital (including learning and capacity building), investment and technology (including technological innovation) for resilience as main thematic domains.

Disturbance Source

Another discriminator is the source of the disturbance that is envisioned—if applicable. We differentiate between studies that frame disturbances as originating from within the system—and which are thus an intrinsic part of the defined system and its dynamics—vs. those that identify a disturbance as external to the system. Especially in the latter case, shocks are often assumed uncontrollable, whereas with internal shocks part of the resilience to that shock might lie in altering the system or its variables such that the shock itself is mitigated in conjunction to mitigation its impact on the system.

Disturbance Phase

The last resilience related characteristic that we identified is the phase of the disturbance or shock. We distinguish between studies that identify disturbances as something that is foreseen (to potentially happen in the future), to cope with (in the present) or to recover from (after the shock has happened) (Hollnagel et al., 2006). A similar differentiation by Shin et al. (2018) identified a system's adaptive capability, withstanding capability (mainly relevant for disturbances that are foreseen), adsorptive capability (to cope with present shocks) and restorative capacity (to recover from shocks). The disturbance phase also has a bearing on which phase of the adaptive cycle the system is in—its exploitation, conservation, release or re-organization phase (Holling, 2001).

Spatial Scale and Case Study

Both for characterizing the WEF nexus and resilience, the spatial scale of assessment is important and differs across studies. Especially for SES resilience and transformation, cross-scale dynamics and interactions with both lower and higher-level systems imply that resilience at one level of assessment may affect resilience in other levels (Holling, 2001; Gunderson and Holling, 2002). If the system is relatively small or narrowly defined, there is a risk of getting stuck in a particular domain of attraction and missing context; if, in contrast, the system is exceedingly large (e.g., the Earth System), complexity may be overwhelming and moreover—if that is part of the objective—management or governance decisions are typically not made at this level (Musters et al., 1998). The spatial scale (or grain) of the study thus matters and differs across current literature. We distinguish between local (meaning sub-national), national, regional (meaning supra-national) and global scales of assessment. Since spatial scale often becomes evident from case studies, we checked reviewed publication on the presence or absence of a case study as well.

Mapping the Research Landscape

Our scoring of reviewed publications that conflate nexus and resilience concepts reveal that half the studies scope the nexus as a connotation of linked water, energy, and food systems, while the other half scopes the nexus as an approach (**Figure 1**). If studies place more emphasis on one WEF component over the others (40%), it is on the water component (20%). This could be explained by the roots of the nexus originating from the water space. Most publications, however, treat the nexus as an integrated whole, placing equal emphasis on water, energy, and food components in their research (60%). In terms of the level of integration, however, we find that the highest level (i.e., incorporation) is only adopted by 21% of the publications. Coles and Hall (2012), for example, provide a clear overview of what such incorporation can entail in a WEF security context.

Most publications scope resilience as some form of SES resilience (53%), vs. 13% on engineering resilience and 34% on transformation. Typical examples of SES resilience can be found in the study by Gragg et al. (2018), who set out to generate environmental, social as well as economic perspectives and practices on rapidly urbanizing food systems, while identifying key drivers and their cross-scale interactions across the urban WEF nexus; of engineering resilience in Ajami et al. (2008) who developed a hydrological reservoir model and indicated the recovery speed of the system from a state of failure, considering a range of rules on how to operate the reservoir; of transformation in Hoolohan et al. (2019) who built scenarios that capture complexity and multidimensionality of changes across the WEF nexus in order to facilitate transformative action.

Two-thirds of the publications deal with specified resilience ('of what to what') and one-third with general resilience. With regards to specified resilience in a nexus context, Jarvie et al. (2015) provide an example in studying resilience of USA farming system to a clearly identified shock, i.e., disturbed phosphorus cycles. McCormick and Kapustka (2016) elaborate on general resilience in a nexus context, arguing to ask resilience-related questions when evaluating alternative environmental policy options, regardless the environmental issue or shock of concern.

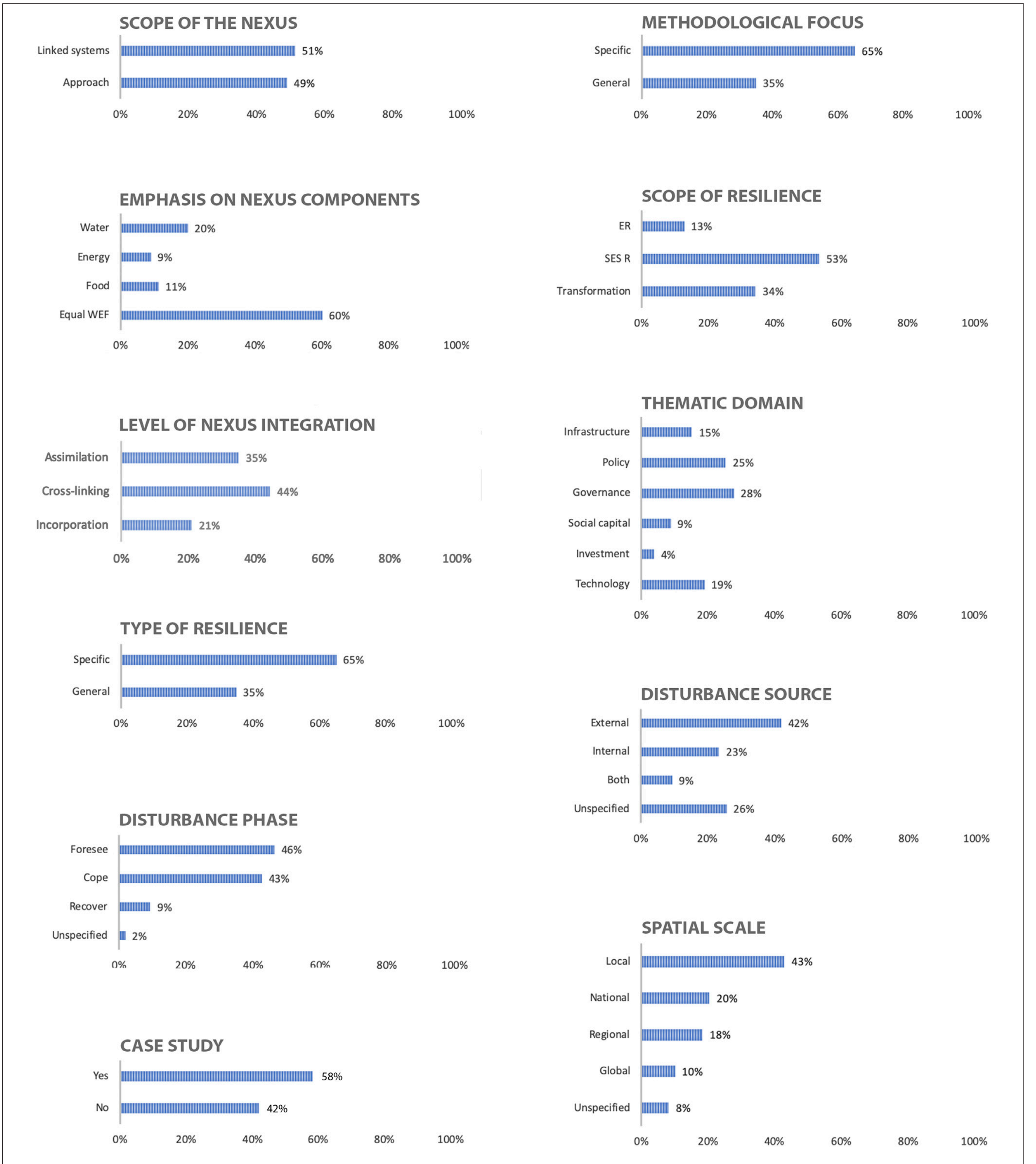

FIGURE 1 | Cross-section of the research landscape across each of the identified nexus and resilience characteristics.

Regarding the methodological focus, 37% of the reviewed publications focus on conceptualizing or developing theory on resilience in a WEF nexus context. Thirty per cent of studies aim at building or managing for resilience. Fewer studies model (20%) or measure (13%) resilience. Representing modeled resilience, Govindan and Al-Ansari (2019) presents a computational framework that incorporates 'algorithmic resilience thinking' toward adaptive and robust WEF

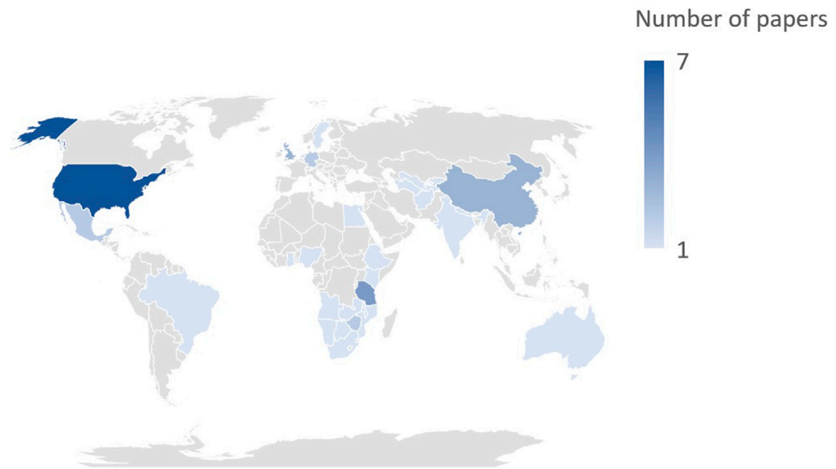

FIGURE 2 | Distribution of local and national case studies over countries.

systems. Regarding measuring resilience, Dal Bo Zanon et al. (2017) measured resilience in terms of the amount of nutrients that could be recycled, in their study evaluating the contribution of floating systems that produce algae, food and biofuel to resilience of urban areas.

Divisions across thematic domains reveal that most publications are in the governance (28%) and policy (25%) domains, followed by technology or innovation (19%) and infrastructure (15%). Social capital, which includes learning and capacity building, is a major topic in 9% of the publications. Only three studies (4%) deal with investment, including Al-Saidi and Saliba (2019)'s study on investments mitigating (WEF) resource supply risks in the Gulf region and Bennett et al. (2016)'s study into the general role of investments in both engineered and natural infrastructure to increase resilience of WEF systems. These finding depart from those of generic WEF nexus review studies by, among others, Albrecht et al. (2018), who found that studies focusing on governance and policy are underrepresented. The difference may be explained by the prevalence or importance of adaptive governance in resilience studies, skewing the thematic distribution of the nexus-resilience sub-section of WEF nexus literature.

In terms of the source and phase of disturbances against which to build, manage, understand, measure or model resilience, most studies that specify the disturbance (74%) identify it as external (42%). Typically listed external shocks are climate change (and related disturbances such as altering rainfall patterns, weather volatility and droughts, see e.g., Adegun et al., 2018); resource supply limitations including water, nutrients and land (e.g., Keairns et al., 2016); and migration (e.g., Lambert et al.. 2017). Some authors internalize shocks that are perceived as external by others, such as Schreiner and Baleta (2015) does with variability in resource supply. Other typical internal disturbances are habitat loss (e.g., Githiru et al., 2017) and urban transformation (e.g., Rohracher and Kohler, 2019). Most studies anticipate foreseen disturbances (46%) or cope with present disturbances (43%). Nine per-cent of studies focusses on recovering from shocks suffered in the past, such as soil erosion in a study by Blake et al. (2018).

The local scale is targeted in 43% of the publications, while 20, 18, and 10% of the studies focus on the national, regional, or global scale, respectively. A case study is included in 58% of the publications investigated. **Figure 2** highlights the countries in which either local or national case studies are located, or which are explicitly mentioned as locality of interest. Eighteen of 48 reported case studies refer to Africa, four of which to Tanzania. Seven studies focus on the USA, three on the United Kingdom and three on China. Not listed in **Figure 2** are regional studies, which in our pool included Europe, the Gulf region, West Africa, Southern Africa, and Asia.

Figure 3 shows cross-sections of the research landscape across combinations of some of the characteristics discussed individually above. Combining the resilience thematic domain and the level of nexus integration, we find that most thematic domains adopt a cross-linking level of integration of the WEF nexus (**Figure 3A**), accounting for 41–67% of each domain's studies, except for technology (27%). Examples are Allan et al. (2013) for the policy domain and Al-Saidi and Saliba (2019) for the investment domain. Assimilation is prevalent in most domains as well (30–42% of studies across domains), but to a lesser extent in the social capital domain (14%). No studies in the investment and infrastructure domains integrate the nexus at the highest level of *incorporation*.

Combining the scope of resilience with thematic domains reveals that SES resilience (**Figure 3B**) is the most common scoping for policy, governance, social capital and investment studies (61–75%), such as those by Blake et al. (2018), Givens et al. (2018) and Howarth (2018). Technology or innovation studies, on the contrary, are most interested in resilience as transformation (56%), e.g., Florentin (2019) and Song et al. (2019). Not surprisingly, infrastructure is most often the topic of engineering resilience studies (36% of infrastructure studies adopt an engineering resilience scope), such as in the studies by He et al. (2019) and Karan et al. (2019).

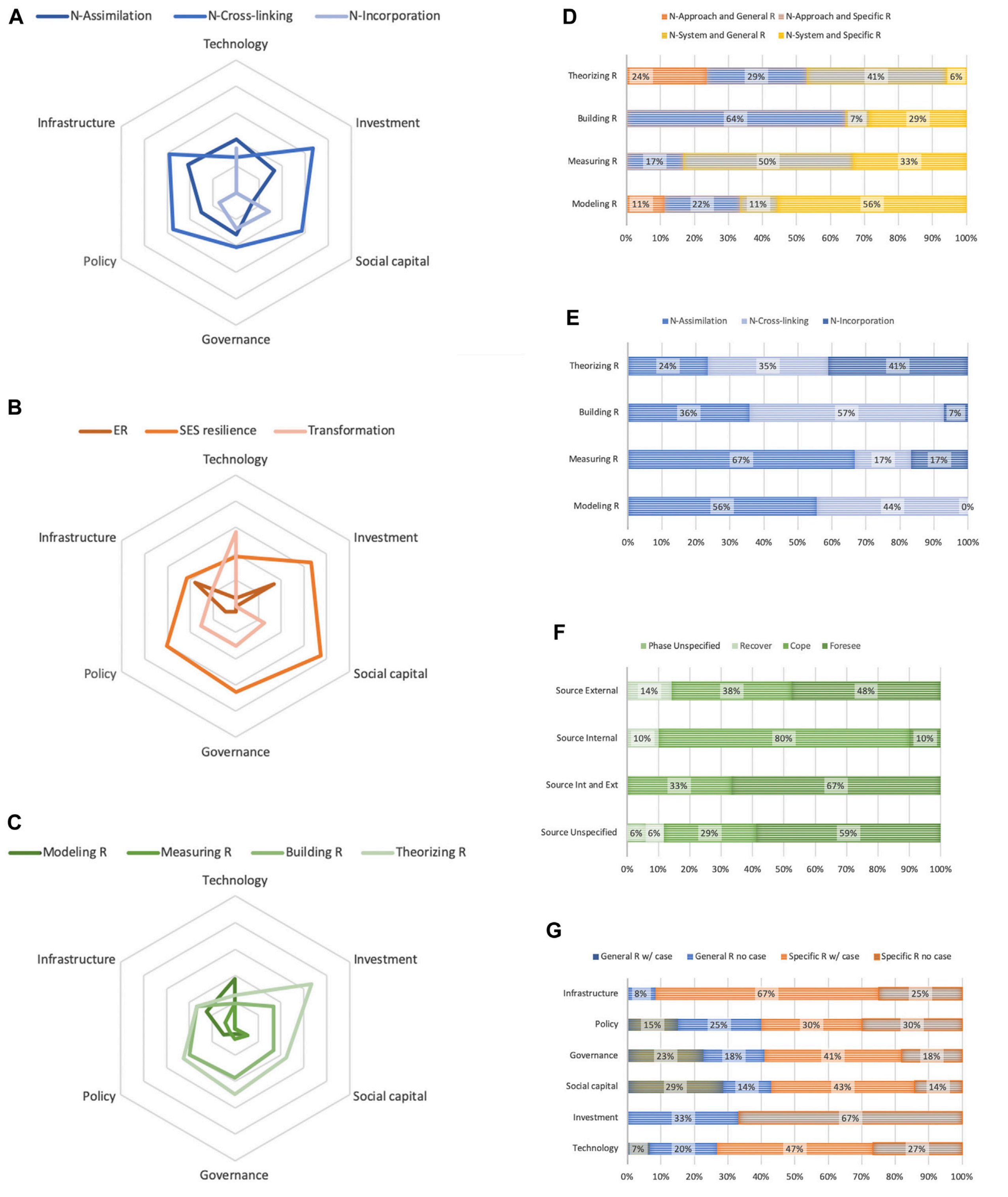

FIGURE 3 | Cross-section of the research landscape across multiple nexus and resilience characteristics. Abbreviations: engineering resilience (ER), nexus (N), resilience (R), social-ecological systems (SES).

The comparison of the methodological focus with the thematic domain of resilience studies (**Figure 3C**) reveals that infrastructure studies chiefly model (25%) or build (33%) resilience, e.g., Amjath-Babu et al. (2019) and Haupt (2019); studies in the policy and governance domains theorize (45 and 50%, respectively), e.g., Uden et al. (2018) and Karlberg et al. (2015) or build resilience (40 and

38%, respectively), e.g., Mpandeli et al. (2018) and Antwi-Agyei et al. (2018); social capital and investment themed publications theorize about resilience (44 and 67%, respectively), e.g., Givens et al. (2018); and technology focused research mainly models (38%), e.g., Johnson et al. (2019) or measures resilience (19%), e.g., Schlor et al. (2017).

Figure 3D starts from the methodological focus and intersects this dimension with the scope of the nexus and resilience type. We learn that theorizing studies mostly deal with resilience of the general type and the nexus scoped as a system (41%), e.g., van Vuuren et al. (2015). Studies set out to build resilience, on the other hand, mostly build resilience 'of something to something'—i.e., specified resilience—while taking a nexus approach (65%), e.g., Pardoe et al. (2018). The lion's share of resilience measuring and modeling studies interpret the nexus as a system, irrespective the resilience type, e.g., Schlor et al. (2018).

Taking again the methodological focus as a basis and comparing it across the level of nexus integration, **Figure 3E** shows that 41% of studies theorizing resilience assume a high level of nexus integration. This share is much lower for resilience building (7%) and measuring (17%) studies, and even nil in resilience modeling studies. In these latter categories, nexus integration is mostly at the level of cross-linking (building resilience, 57%) or assimilation (measuring resilience (67%) and modeling resilience (56%)). This could be explained by the observation that theorizing studies typically emphasize the complexity of the systems they investigate—a complexity most often found at higher levels of nexus integration (cf. Scott et al.. 2018). More pragmatic resilience measuring and modeling studies, in contrast, generally need to simplify systems to make them manageable. This seems to be more feasible for lower levels of nexus integration (cf. Gomo et al., 2018 and Namany et al., 2019).

With regards to the intersection of source and phase of the disturbance(s), **Figure 3F** illustrates that there is just a small percentage of studies that specify neither source nor phase (6%)—which could be expected particularly for general resilience type studies. Authors that identify a disturbance externally typically try to cope with this disturbance in the present (38%) or anticipate this disturbance to potentially happen in the future (48%). Internally identified disturbances, in contrast, overwhelmingly occur in the present (80%) where attempts are made to cope with (and adapt to) them.

Figure 3G revisits the thematic domain once more, but in this instance in combination with the type of resilience, and whether the publication includes a case study. We learn that few domains employ general resilience in combination with a case study (policy domain 15%, governance 23%, social capital 29%), e.g., Gragg et al. (2018) and Uden et al. (2018). In contrast, studies that focus on specified resilience by and large do have a case study across domains, particularly in the infrastructure domain (67%), e.g., Romero-Lankao et al. (2018).

TOWARD A RESEARCH AGENDA

Mapping the research landscape demonstrates that not every dimension of resilience and nexus research has received equal attention. The landscape thereby lays bare potential knowledge gaps that may warrant further scrutiny. The reviewed publications also provide recommendations for future research but given the divergence of the research landscape these recommendations are often context and project specific. At the risk of overgeneralizing, we identified the following five research avenues through synthesizing landscape lacunas and publication's recommendations. **Table 2** presents an overview of example research questions per line of inquiry.

Improving the Understanding of Resilience Across the WEF Nexus

When Holling (1973) introduced resilience thinking, he studied the resilience of fish levels in a lake to fishing. Translated to our analysis, he studied specified resilience of a local, siloed water-food (sub-)system to an external disturbance. Deliberating the implications for larger, more complex systems, he wondered if we were ever able to see beyond the boundaries of local domains of attraction and understand the configuration of forces caused by both positive and negative feedback relations. This would "require an immense amount of knowledge of a system and it is unlikely that we will often have all that is necessary" (Holling, 1973). While many studies since have shed light on the matter, there is still a clear need to better grasp resilience in the WEF nexus.

First, there is a need to better understand the WEF nexus dynamics itself. As Leck et al. (2015) warned, siloed WEF systems are already complex to assess, let alone taking a nexus perspective or applying resilience thinking. The study by Guillaume et al. (2015) illustrates this cross-system complexity in a case from Central Asia, where they observed that changes in the water system were mainly driven by interventions in other systems, such as the loss of ecosystems. They therefore stress the importance of paying close attention to which (sub-)systems to include or exclude from any nexus assessment, and what boundaries to assume.

A second opportunity lies in better understanding the place of resilience thinking in these cross-system WEF nexus dynamics. A popular yet partial means to obtain insights on resilience of cross-system dynamics is to study synergies and tradeoffs between WEF systems (Jarvie et al., 2015; Cader et al., 2016; Deryugina and Konar, 2017; He et al., 2019). However, most of these assessments consider synergies and tradeoffs only between subsystems within the larger WEF nexus and overlook cross-system resilience linkages. Grafton et al. (2016), for example, show how increasing food production resilience may (unbeknownst to the managers) erode the resilience of water systems. This indicates a niche for more comprehensive cross-sectoral investigations, taking a broad scope of resilience across a well-defined nexus.

Third, insights may be gained by including a broader set of thematic domains. Our characterization of the research landscape also found that most studies focus on one or two thematic domains, and do not account for developments, incentives or dynamics in other domains. de Loe and Patterson (2017), for example, observed that although resilience thinking pays attention to external drivers such as climate change and teleconnections, it remains unclear to what extent water resilience accounts for connections between water and other sectors, since studies tend to emphasize processes that are internal to water governance over external connections that can influence water governance. In another study, investigating

TABLE 2 | Overview of example research questions per identified research avenue.

Research avenue	Example research questions
Improving the understanding of resilience across the WEF nexus	How much water and land is needed to produce food and energy for all by 2050? To what extent will renewable energy mixes based on biomass affect resilience of water provision and food production systems? How can policies that promote health and nutritional diets concurrently reduce carbon and water footprints, by advising foodstuffs with low associated energy and water use/pollution? To what extent are international and interprovincial trade networks reflective of local WEF scarcity/insecurity levels? How can short-term disturbances such as droughts, crop pests and animal diseases, act as a catalyst for long-term WEF system transformation? How can (inter)national funding organizations support interdisciplinary research lines across the broad resilience/WEF nexus spectrum to boost collaboration on holistic projects?
Tools and indicators	Which indicators can express resilience of urban WEF systems and what are their constraints for applicability in urban planning? To what extent can agent-based modeling techniques capture resilient behavior patterns of smallholder farmers in WEF nexus simulations? How can remote sensing techniques measure and monitor resilience of WEF nexus systems over large spatial and temporal scales? Which forms or platforms of data collection and sharing fit best with general practices currently used in water, energy, and food domains?
Bridging the implementation gap	How can examples of successfully negotiated bilateral treaties on sharing proceeds of offshore wind parks inspire transboundary water pricing and sharing? What is the role of financial institutions in building resilient WEF systems and to what extent do their investment policies hamper or hasten implementation of resilient WEF projects? Which institutional structures facilitate experimentation and learning in local waterboards who have indirect responsibilities for energy and food systems? What are best practices of governing for resilience in local WEF systems in public private partnerships?
Integrating resilience and nexus thinking	What further lessons can resilience and WEF nexus scholars learn from systems thinking and integrated assessment? In which contexts (e.g., environmental policy, risk management, security studies) would a shared resilience-nexus thinking heuristic be advantageous and which key elements of each school of thought would such a heuristic include or exclude? To what extent can resilience and WEF nexus thinking help achieve the UN's Sustainable Development Goals (most notably SDGs 2, 6 and 7 on food, water, and energy, respectively)?
Beside and beyond resilience	In promoting resiliency, how are social, environmental, and economic costs incurred by diversifying national WEF sources (e.g., by building a hydroelectric dam) distributed fairly over stakeholders? What different WEF outcomes can be expected when policymakers and practitioners in natural resources management would focus solely on building resilience vs. on improving efficiency, sustainability, or equity as a guiding development principle?

risks of climate extremes to WEF security in cities, Romero-Lankao et al. (2018) stress the need to consider the role of technology in mitigating impacts, while Uden et al. (2018) warn in their study on transforming agricultural landscapes that neglecting considerations from financial, technological and policy domains may create unsustainable feedbacks between WEF systems. These cross-domain feedbacks may form so called rigidity traps, which impede transformation by locking the nexus into an undesired trajectory. However, these traps are typically ill-understood. Insights from resilience thinking, which emphasizes cross-domain feedbacks and dynamics, might help analyze and avoid such traps.

Fourth, we identify a knowledge gap pertaining to cross-scale dynamics, or panarchy. One of the key lessons from resilience thinking is that we need to understand the implications of cross-scale dynamics or interventions that operate at different scales for the system as a whole (Anderies et al., 2013). In fact, even the nature of the challenges under investigation depends on the scale of the assessment. However, our mapping of the research landscape reveals that many studies—both regarding the scope of resilience and the level of nexus integration—largely overlook this spatial multi-dimensionality. These findings resonate with other observations. For instance, Florentin (2019) found that cross-scale dynamics of municipal (energy) utilities in Germany are insufficiently accounted for. Meyer (2020) argued that studies on resilience of food systems in low- and middle-income countries are largely concerned with primary production only, mostly quantify resilience at the global scale while failing to quantify resilience at the regional scale. Falkenmark et al. (2019) called for further research to understand how the erosion of water resilience at local and regional scale may potentially interact, cascade, or amplify through networks of the Anthropocene.

Fifth, we highlight a knowledge gap relating to resilience scoped as transformation. Despite our finding that one third of the reviewed publications interprets resilience as transformation (**Figure 1**), most studies remain shallow in their assessment, and, moreover, are not always explicit about the system whose transformation they seek to study. These observations echo similar concerns by early studies on resilience as transformation by Folke et al. (2010) and more recently by D'Odorico et al. (2018). Transformation often implies interventions be made in WEF systems; hence it is important to understand how these interventions (e.g., policies aiming to reduce trade-offs) will modify system dependencies. These modified dependencies may create new, perhaps unforeseen, trade-offs (Guillaume et al., 2015; Tu et al., 2019).

To capture the required holistic perspectives listed above, interdisciplinary collaboration across WEF sectors should be improved. Clearly, the level of nexus integration matters, as assimilation requires fewer interdisciplinary connections than incorporation does. However, our analysis of the research landscape shows that few studies employ the highest level of nexus integration (incorporation, **Figure 3A**), which may be a consequence of limited collaboration across relevant disciplines. It has been noted that collaboration is still hampered by fundamental gaps between the evidence bases of different disciplines, not in the least due to differences in conceptualizing resilience (de Grenade et al., 2016; Howarth and Monasterolo, 2016; Blake et al., 2018).

Tools and Indicators

"Measuring resilience is essential to understand it" (Pimm et al., 2019). However, developing tools and indicators to measure, monitor, model and evaluate resilience in the WEF nexus remains as an under-represented theme in the current research landscape. This observation can be explained partially by the complexity of both concepts, which makes it difficult (if not impossible) to capture resilience in the nexus using a limited number of methods and indicators (Quinlan et al., 2016; Hoekstra et al., 2018). Conceptual variations and subsequent differences in operationalization of both concepts are another potential explanation for this research gap (Givens et al., 2018).

Several tools—meaning methods, models, and frameworks—are being developed to overcome this gap. We identify two directions of development. The first is the development of tools to improve the understanding of cross-sector, cross-scale, cross-domain, and complex dynamics. Proposed examples are scenario building (e.g., Hoolohan et al., 2019), trade-off analysis (e.g., Cader et al., 2016), integrated assessment modeling (e.g., Johnson et al., 2019), environmental footprinting (e.g., Vanham et al., 2019; Hogeboom, 2020) and agent-based modeling (e.g., van Voorn et al., 2019). The second direction is to develop tools and methods that support more consistent policy formulation. Examples include decision-making frameworks and mixed method approaches (e.g., Knox et al., 2018; Namany et al., 2019), and participatory, stakeholder and networking methods (Karlberg et al., 2015; Hoolohan et al., 2019).

Despite ongoing developments, it remains unclear which tool can be applied in which resilience or nexus context. In this regard, Zhang et al. (2018) made a preliminary effort by identifying eight nexus modeling approaches and providing guidance on their selection within appropriate nexus settings.

Another open question is to what extent these tools can potentially be scaled-up, used in conjunction, or be integrated. A recent study by Vinca et al. (2020), for example, presents an new open modeling platform that integrates multi-scale nexus resource optimization with distributed hydrological modeling, and "provides insights into the vulnerability of water, energy and land resources to future socioeconomic and climatic change and how multi-sectoral policies, technological solutions and investments can improve the resilience and sustainability of transformation pathways while avoiding counterproductive interactions among sectors."

Broadly accepted indicators for resilience are rare, as are those that pertain to the WEF nexus. Some examples in our pool of reviewed publications are the Nexus City Index and the WEF nexus index (Schlor et al., 2018, 2017), and an event-specific resilience measure for WEF infrastructure (Lambert et al., 2017). Caution is warranted, however, in developing overarching indicators. As Quinlan et al. (2016) observes: "Measuring and monitoring a narrow set of indicators or reducing resilience to a single unit of measurement may block the deeper understanding of system dynamics needed to apply resilience thinking and inform management actions."

Finally, many authors point out that even if tools and indicators are available, challenges remain in data availability and collection options (Coles and Hall, 2012). More efforts are thus needed to collect data across studies and to develop new approaches that facilitate data collation and sharing.

Bridging the Implementation Gap

Many scholars critique the lack of practical application of both nexus and resilience thinking (particularly pertaining to SES resilience and transformation) (Bizikova et al., 2013; Sellberg et al., 2018). Our mapping exercise supports the argument that there is a divide between two major types of studies. On the one hand, practice-oriented building, measuring and modeling studies often employ specified (engineering) resilience of a particular (local) nexus system to a known disturbance, showcased by a case study. On the other hand, theoretical studies on general (SES) resilience embrace the complexity of WEF systems incorporated across scales, but they lack practical grounding.

Identified barriers to implementation of the nexus as an approach and higher levels of nexus integration are similar to those listed for practical uptake of resilience thinking. Barriers include a lack of data, knowledge and observability that match the level of complexities involved (Gomo et al., 2018); physical challenges of managing resources over a large area (Schreiner and Baleta, 2015); and a lack of public and private investments (GARI, 2016; Howarth and Monasterolo, 2016).

Most often, however, governance is underscored as impeding factor for practical uptake of resilience and nexus thinking. Reported barriers include institutional contexts that hinder flexibility, experimentation, learning and collaboration (Dietz et al., 2003; de Loe and Patterson, 2017); a lack of coordination among institutions and agencies, both across scales and across domains (Antwi-Agyei et al., 2018; Stringer et al., 2018); issue prioritization that is missing or left to policymakers' ad hoc choices (Al-Saidi and Elagib, 2017); lacking examples of best practices to take as an example, particularly for commercial applications (Keairns et al., 2016); and an absent heuristic for resilience management (Grafton et al., 2019). Given these barriers, Weitz et al. (2017) advocate to develop shared principles to guide trade-off negotiations and to emphasize that policy coherence be viewed as a learning process rather than as an outcome. Both governance and non-governance barriers to implementation, however, are challenging and not easily overcome.

Integrating Resilience and Nexus Thinking

We started this study by presenting resilience and nexus thinking as two promising frames to help deliver on the grand development challenges of reaching WEF security for all while sustaining that security under threats. In the diverse research landscape that conflates the two schools of thought, we observed a pronounced distinction between the starting frame scholars assumed for their assessment. Some—particularly but not exclusively those involved in public policy debates—assumed a nexus approach, which they applied to enhance (specified) resilience of linked WEF systems (e.g., Pahl-Wostl, 2019). Others, on the other hand, started from a (predominantly academic) resilience perspective, in which water, food and energy systems happened to be the (SES) arena where adaptations and transformations take place (e.g., Uden et al., 2018).

While historical developments in different research arenas, conceptual variations, and personal preferences can explain why some authors start from a nexus and others from a resilience frame, we also observed a great deal of overlap in the concepts and ideas employed in both schools of thought. This is particularly the case for studies that scope resilience as SES resilience or transformation and the nexus as an approach with a high level of integration. Elements common to both the nexus and resilience thinking are the application of systems thinking, taking an integrative management perspective and considering complex dynamics across scales, domains and sectors (cf Al-Saidi and Elagib, 2017). Also the notion of enhancing security against shocks or risks appear to be a common connection between nexus and resilience discourses (cf Al-Saidi and Saliba, 2019). Given these similarities, a sensible question is to what extent the two frames could or should be integrated or mutually embedded (cf Grafton et al., 2016; de Grenade et al., 2016; Scott et al., 2018).

Research addressing the integration question can for example investigate areas in which greater mutual interaction could provide enriched insights (Howarth and Monasterolo, 2016). Beck and Walker (2013), for example, distilled lessons from resilience thinking to be applied in nexus debates, including the need to increase diversity, and tolerating soft redundancies and inefficiencies of function within a system. How this translates to practice, however, is yet unclear. Another question is to what extent embedding resilience thinking in nexus thinking will change to role of e.g., systems thinking, or the current emphasis on water as first among equals (**Figure 1**).

Alternatively, investigations can look into fully merging the two frames. The most comprehensive attempt to our knowledge is by Stringer et al. (2018). Their integrated nexus-resilience thinking framework highlights three principles: unpack, traverse, and share. Here, unpack refers to unpacking relationships and interactions in SESs to better understand and structure (WEF security related) issues; traverse refers to traversing temporal and spatial scales, sectors, stakeholders, and ways of knowing to detect nonlinear dynamics and unpredictable outcomes; and share refers to sharing knowledge, learning, and experience to empower stakeholders involved.

Beside and Beyond Resilience

Studies that build, model or measure resilience in the WEF nexus by and large take a normative stance toward the concept of resilience, portraying resilience as a desired capability of WEF systems or a welcome feature of the WEF nexus approach. However, these same studies are less explicit about both the cost of achieving resilience and potential alternative outcomes, processes or principles that are being foregone by adopting a singular focus on resilience (cf Anderies et al., 2013; Moser et al., 2019). We see a need to address the tradeoffs and synergies between multiple development objectives and their implications, including control, efficiency, robustness, sustainability, equity, and fairness, to enrich policy design frameworks with perspectives from beside and beyond the resilience rationale.

Givens et al. (2018), for example, found that a resilience focus applied to the WEF nexus can strengthen the status quo imposed by stakeholders that are already in power, leading to starkly unequal outcomes. Researchers are therefore heeded to critically examine the desirability of WEF system resilience, "which presupposes the value of maintaining the system, rather than aiming for system change (...) If the desirability of maintaining the system as a whole is questioned, identifying system functions may be an alternate way to identify what is desirable to sustain and what is meant by adaptation vs. transformation. However, focusing on a system's function tends to ignore inequality and conflict in the system by not attending to who gets to identify what functions are valued and benefit most from valued functions" (Givens et al., 2018). Similar pleas to better incorporate the principles of equity and fairness in WEF nexus management are voiced by Schlor et al. (2018) and Fainstein (2018).

It is said that the best way to build resilience of a forest to fire is to burn it. However, in a WEF nexus context—as is the case in other SES contexts—the amplitude of shocks cannot be too large, even if it promises to build additional system resilience. Hoekstra et al. (2018), therefore, argued to pay attention to the merits of control as a guiding principle for managing (WEF) systems under uncertainty. Their study provides an illustrative framework for contrasting and reconciling control and resilience principles.

CONCLUSION

New ways of thinking on natural resources governance are needed for the 21st century, if we are to provide basic human necessities of water, energy, and food to all, in an environmentally sustainable, economically viable and socially inclusive manner that is moreover capable to cope with shocks and disasters. This paper distilled key characteristics of two such paradigms—the (WEF) nexus and resilience thinking—that are said to have the potential to deliver on these grand development challenges. In the research landscape that is constituted of publications that conflate both framings, we observed pronounced differences regarding the nexus' nature, scope, emphasis and level of integration, and resilience thinking's scope, type, methodological and thematic foci.

We found that the landscape is divided over whether the nexus refers to (simply) a connotation of linked systems, or to a management approach. Moreover, while many studies on the nexus strive to interconnect the three WEF nexus components of water, energy and food, few studies integrate the nexus to its fullest extent. Resilience in these studies is characterized chiefly as specified SES resilience, where a local subset of the WEF nexus forms the SES arena of interest. In contrast to the generic body of literature on the WEF nexus, governance and policy issues are the thematic domains most often addressed in our pool of reviewed publications. One third of the reviewed publications scope resilience as transformation, particularly those addressing themes related to technology and innovation. The level of analysis attained, however, is typically quite shallow, particularly lacking depth in how transformative action may alter system dynamics. Not surprisingly, infrastructure is the dominant topic of interest in engineering resilience studies. While both social and financial capital are ascribed important roles in building resilience across (the governance of) the nexus, few studies focus on the role of learning, capacity building and investments.

Knowledge gaps and opportunities found by our mapping exercise unveiled five overarching avenues for future research:

- While plenty publications develop theories and conceptual frameworks, we see a clear need to improve the understanding of resilience across the WEF nexus, in all its cross-sectoral, cross-domain and cross-scale complexity. This calls for an interdisciplinary research approach that brings together scholars from disciplines relevant to both nexus and resilience discourses.
- Few studies measure and model resilience, giving rise to the opportunity to develop tools and indicators that measure and monitor resilience in the WEF nexus. Ideally, these tools and indicators are designed such that they can be scaled-up, used in conjunction or be integrated across various nexus contexts.
- The role and structure of governance in particular warrants further scrutiny, as it is repeatedly mentioned as a barrier to implementing resilience thinking in a WEF nexus context.
- A significant overlap exists in the concepts and ideas employed in both schools of thought, particularly in studies that scope resilience as SES resilience or transformation, and the nexus as an approach with a high level of integration. Future research may reveal the extent to which integration is possible or desirable, as well as areas in which greater mutual interaction and exchange could provide enriched insights for natural resources governance.
- There is no panacea to natural resource governance (cf Ostrom, 2007). In emphasizing resilience thinking in WEF nexus governance, other governance or development principles, such as control, efficiency, robustness, sustainability, equity, and fairness, may be overlooked. A knowledge gap remains in understanding tradeoffs and synergies between such different principles and addressing their implications for WEF nexus governance and policy making. Widening the scope could enrich policy design frameworks with perspectives from beside and beyond the resilience rationale.

AUTHOR CONTRIBUTIONS

RH and AN conceived the conceptual design and methodology of the article. RH and MD carried out the formal (review) analysis, which was validated by all co-authors. RH wrote the manuscript with contributions from all co-authors.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2021.630395/full#supplementary-material.

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Farmers' Assessments of Their Cooperatives in Economic, Social, and Environmental Terms: An Investigation in Fujian, China

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This study is the first to empirically investigate whether farmers' assessment of their cooperatives' environmental efforts is related to their satisfaction with the cooperatives, in addition to their assessment of the cooperatives in economic and social terms. A survey was conducted among a randomly selected sample of 211 members of 63 farmer cooperatives in Fujian Province, China. Binary logit analyses were conducted to test three theoretically derived hypotheses. There was a positive relationship between member satisfaction with the cooperatives and farmers' assessment of the cooperatives' environmental actions, although the cooperatives' economic and social contributions were even more appreciated. Consequently, at least under the prevailing circumstances, member satisfaction with their cooperatives is positively associated with the farmers' view of the environmental ambitions of their cooperatives.

Keywords: ecology, member involvement, member satisfaction, social capital, standard of living, sustainability

INTRODUCTION

Agricultural production has a major impact on the environment. Thus, environmental gains can be expected if farmers choose environmental-friendly production practices, especially if the members of a farmer cooperative support their cooperative's environment protection policy. The present study investigates how farmer members of Chinese cooperatives consider their cooperatives' environmental ambitions in comparison with the economic and social benefits that they get from the cooperatives. Thus, this study comprises environmental, economic, and social sustainability, all of which are specified in the Brundtland Report. The United Nations established this commission (formally "The World Commission on Environment and Development"), which presented its report "Our Common Future" (WCED, 1987).

There is a rich volume of literature about farmers' satisfaction with their cooperatives (Hernández-Espallardo et al., 2013; Arcas-Lario et al., 2014; Grashuis and Cook, 2019). Many researchers have testified to a strong relationship between members' satisfaction with their cooperatives and their view of the economic and social benefits of cooperative membership (Borgen, 2001; Feng and Hendrikse, 2008; Morfi et al., 2015; Morfi et al., 2021). There may, however, also be a relationship between member satisfaction with their cooperatives and their view of the cooperatives' environmental ambitions.

To the best of our knowledge, the present study is the first empirical investigation into whether member satisfaction with cooperatives is related to members' view of their cooperatives' environmental efforts. Only a few previous studies have mentioned that farmers may involve themselves in cooperatives that strive for environmental protection (Slangen and Polman, 2002; Van Dijk et al., 2016). Because farmers and farmer cooperatives work with biological production, which implies environmental consequences, cooperatives may have an opportunity to reduce the environmental impact of member and cooperative production (Lokhorst et al., 2011; Mills et al., 2017). Chinese agriculture is no exception. Because of intensive production on small lots, one farmer's production affects other farmers and the surrounding community, and there is a risk that the individual farmer cares mainly about his or her own production results while caring less for the community. Hence, an institutional arrangement of cooperatives can be a vehicle for reducing environmental problems (Franks and Emery, 2013; Riley et al., 2018).

Chinese farmer cooperatives have generally small memberships and are village-based units. There are social relationships within an existing membership as the members know each other, communicate and have a common set of norms. Neighboring farmers know that they are mutually dependent on each other. Thus, already existing cooperatives can quite easily extend their present activities to comprise a policy of environmental protection.

The aim of this study is to explore the relationship between Chinese farmer satisfaction with their cooperatives and their perceptions of the cooperatives environmental terms, as opposed to their perception of the cooperatives in economic and social terms. This study extends knowledge about the raison d'être of cooperatives beyond the existing literature, which explains the economic and social importance of cooperatives in terms of transaction cost theory, social capital theory, and other theoretical approaches (Fulton, 1995; Holmström, 1999; Valentinov, 2004a, 2007; Cook and Grashuis, 2018). Extended knowledge about cooperative members' views of their cooperatives' environmental work would be valuable when cooperative decision-makers are trying to adapt the cooperatives' activities to the wants of their memberships. Furthermore, such knowledge may be valuable when governments design and implement programs for environmental policies, which are related to agricultural production.

Section "**The Development of Chinese Farmer Cooperatives**" presents the development of farmer cooperatives in China, especially how the cooperatives have expanded their range of activities during recent years. Section "**Conceptual Framework**" offers a conceptual framework that explains possible rationales for agricultural cooperatives. The section thus comprises theoretical arguments for why cooperative members may be motivated by what their cooperatives offer in economic, social, and environmental terms. Section "**Methodology**" presents the methodological issues concerning the choice of variables, data collection techniques, and statistical methods. Section "**Findings**" comprises the findings and interpretations of the findings. Last, Section "**Conclusions**" presents conclusions.

THE DEVELOPMENT OF CHINESE FARMER COOPERATIVES

Farmer Cooperatives in China

Rural reforms at the end of the 20th century in China paved the way for commercialization and marketization in the agri-food sector, but these reforms did not help farmers gain better prices when selling their products and buying farm inputs. To strengthen primary agriculture, a law on cooperatives was introduced in 2007 ("Farmer Specialized Cooperative Law of the People's Republic of China"). During the relatively few years since the law was passed, farmer cooperatives have come to dominate the Chinese agricultural sector. Nearly half of all Chinese farmers are members of cooperatives. By the end of October 2019, the number of registered farmer cooperatives was 2.2 million. However, perhaps only 20% of registered cooperatives are actually in operation because many people register cooperatives to gain financial support from the government and because local governments want to signal success at a higher political level (Sultan and Wolz, 2012; Deng et al., 2016). The general definition of cooperatives applies to Chinese agricultural cooperatives: "In a cooperative, the user is the focal point, with the direct status of user, owner, and control vested in the same individual" (Dunn, 1988, p. 85). Even though Chinese cooperatives fit into this definition, they are different from cooperatives in most other countries (Bijman and Hu, 2011). The Chinese law on cooperatives states that members can be anyone who in any way contribute to the operations of a cooperative. Thus, members could be farmers who supply agricultural products but invest only small amounts of capital, but also those who provide much financial capital but deliver no or only a small amount of products. The former are called "common members" and the latter "core members" (Xu, 2005; Liang and Hendrikse, 2013). Four-fifths of the members are common members.

Even though the two categories of members are mutually dependent upon each other, they have conflicting interests as it concerns the allocation of revenues as product prices and capital remuneration. Therefore, the law on cooperatives stipulates a limit regarding how much dividend may be paid to investing core members vs. the delivering common members (Liang et al., 2015).

The law allows different principles for the allocation of voting power. While the principle of equal voting is the basic one, members with large production volumes may have up to one-fifth of the total number of votes. In reality, however, most power is in the hands of the core members (Liang et al., 2015). They are not only wealthier but are also better educated than the common members are. They also have better networks with various business partners within the value chains as well as with the local and provincial governments. Nevertheless, the cooperatives operate independently from government interference. The membership is voluntary even though there may be social pressures on the farmers within a village.

Cooperatives and the Environment

While the law on cooperatives was intended to raise the farmers' incomes by giving them more market power, cooperatives have later extended their activities to comprise other services (Liu, 2017). For instance, members receive training and advice on efficiency raising production practices. The cooperatives have also involved themselves in financial services (Yu and Nilsson, 2018, 2019). Stimulated by government, farmer cooperatives process member agricultural products into value-added products to be sold at higher prices. Thus, there has been a development in terms of not only the number and size of cooperatives but also in new functions.

Another trend is that the cooperatives introduce social issues. Since 2013, the government has stimulated farmer cooperatives to participate in social services within their villages (Sun, 2017). An example is the financial assistance that some cooperatives provide for their poor farmer members and even nonmembers. Some cooperatives also care about vulnerable villagers, such as the elderly and sick, orphans, and persons with disabilities, many of whom are either acquainted with or related to cooperative members.

Likewise, many cooperatives have involved themselves in environmental services beyond what is required by the governmental environmental requirements. This indicates that cooperatives may constitute an institutional arrangement for rural environmental protection that the government cannot accomplish.

The Chinese constitution and various laws and decrees contain regulations on public participation in environmental protection. The law on environmental protection states, "All units and individuals have the obligation to protect the environment and have the right to report and sue units and individuals that pollute and damage the environment." This principle of public participation is an important legal basis for people to participate in environmental protection in China. The environmental protection clause of the Civil Code was passed as legislation in 2020 in response to the call for mandatory environmental protection in a law from 2014. The Civil Code clause constitutes the main legal basis for the farmer cooperatives' involvement in environmental protection.

Environmental policy in China has not met expectations due to an insufficient involvement of the general public. People who have no direct interests are not enthusiastic about environmental affairs (Zhang and Tian, 2021). If individuals feel that their rights are infringed upon, free rider behavior will result, giving rise to a suboptimal outcome for all individuals.

The focus of China's environmental policy has mainly been on pollution prevention and the control of large- and medium-sized cities and industrial enterprises, while less attention has been paid to environmental protection in rural areas. The rise of farmer cooperatives is successively breaking this deadlock. Through technical guidance and services to members, Chinese cooperatives are raising farmers' awareness of safe production and high-quality products. According to Zhao et al. (2016), technical training provided by the cooperatives helps farmers to follow the safety standard. The cooperatives promote the reduced use of chemical inputs and the reuse of waste. Many cooperatives take on organic production, for example, by purchasing environmental-friendly raw materials such as organic fertilizers.

Just as most Chinese citizens are not involved in environmental issues, it is unlikely that farmers will on their own initiative convert from their traditional production practices into more environment-friendly ones. Such a shift is more probable if it is mediated through a farmer cooperative, where all members have an influence on the decision. If the members know that all other members are obliged to follow a specific set of rules, they are more likely to choose environment-friendly production. People are more willing to accept rules if they have contributed to these rules. The social capital within the small, homogeneous, and geographically limited membership implies a lower risk of shirking. The core members who have invested most money in the production facilities are dependent upon the common members who supply the bulk of the raw products, just as the supplying common members are dependent upon the investing core members. Against this background, it is understandable that an increasing number of Chinese cooperatives have introduced rules for more safe and environmental-friendly production and mechanisms to ensure that members abide by these rules.

CONCEPTUAL FRAMEWORK

The Economic Dimensions of Cooperatives

Economists provide strong theoretical arguments for the view that farmers involve themselves in collective action for economic gains (Ollila, 1994; Hendrikse and Veerman, 2001; Feng and Hendrikse, 2008). This position is also supported by empirical investigations (Ma and Abdulai, 2016; Shumeta and D'Haese, 2016; Mojo et al., 2017; Grashuis and Su, 2019).

A widely accepted theoretical explanation is that farmer cooperatives have the ability to reduce member transaction costs. Without cooperatives, farmers would have difficulties in dealing with powerful business partners (Valentinov, 2007). Because noncooperative business firms are typically superior to the farmers in terms of knowledge, financial status, and other resources, they are in a position to deceive farmers. Many agricultural products are perishable, which means that external buyers may use a hold-up strategy that results in unduly poor conditions for the farmers.

Other researchers present other economic arguments for cooperatives (Schrader, 1989; Van Dijk, 1997). Cooperative members can reach large and lucrative markets, and they are able to build a brand name, which results in higher sales prices. A cooperative can coordinate member production, resulting in higher and more even product quality. Yu and Nilsson (2019) have found that Chinese cooperatives may support member efforts to acquire capital for investments in their agricultural operations. The social character of cooperative societies entails many members and large volumes, and consequently, the cooperatives can enjoy economies of scale (Nilsson, 1998).

Many Western cooperatives have followed a low-cost strategy achieved through waves of mergers. As they have become large, their memberships have become sizeable and heterogeneous, and the business activities have become complex. This has threatened member involvement (Nilsson, 2018). Few Chinese cooperatives have followed a similar strategy concerning large-scale operations. They are small and locally operated, and consequently, the general arguments for farmer cooperatives are likely to apply. This leads to the following hypothesis:

Hypothesis 1: There is a positive relationship between Chinese farmer satisfaction with their cooperatives and the member perception that the cooperatives contribute to a higher standard of living.

The Social Dimension of Cooperatives

To explain the existence of cooperatives, it is necessary to consider not only economic factors but also the social relations between the farmers. A cooperative exists because a group of farmers thinks that a cooperative could benefit them. Thus, it matters how the farmers assess the cooperative business form and that assessment depends on the social context. Most often, local farmers know each other, communicate, and have confidence in each other. Without social interaction, a group of farmers would not run a jointly owned cooperative. One may even claim that the existence of social capital within a cooperative membership is the basis for the cooperative building up financial capital (Valentinov, 2004a, b; Yu and Nilsson, 2018, 2019).

Many previous studies indicate that social factors are related to cooperative member satisfaction (Borgen, 2001; Hansen et al., 2002; Nilsson et al., 2009; Morfi et al., 2021). Communication, social interaction, and collaboration within a cooperative membership positively affect members' views of their cooperative's business activities.

The social relationship between members and cooperatives is dual. One can distinguish between what the cooperative does for its members and what the members do for their cooperative. First, a cooperative contributes to creating cohesion, safety, and stability within the membership (Yu and Nilsson, 2019); the existence of a cooperative affects the mentality within the community of farmer members. Second, the members contribute by participating in the governance of their cooperative; they inform themselves, take part in meetings, and discuss about investments (Morfi et al., 2021). These two aspects of social capital are interdependent but equally important. This leads to the second hypothesis:

Hypothesis 2: There is a positive relationship between Chinese farmer satisfaction with their cooperatives and the member perception that the cooperatives contribute to their social life.

The Environmental Dimension of Cooperatives

Environmental protection often has a public goods character. People may interfere with some collective interests when they act in their individual interests. This phenomenon is often termed "the tragedy of the commons." In such situations, there is a need for collective action, which requires an institutional arrangement to harmonize the incentives of the individuals. According to Ostrom (1990) and Ostrom (1999), the solution to "the tragedy of the commons" is an institutional setting, in which the group of individuals agree upon a set of norms that regulates the negative impact of individual activities (Termeer et al., 2013). A cooperative can provide such an institutional setting for aligning member incentives for producing more in line with environmental requirements. There are no general principles for how such alignments can be achieved, but many empirical studies present various design parameters for the coordination of action within a heterogeneous group of cooperative members (Iliopoulos and Theodorakopoulou, 2015; Tschopp et al., 2018; Dary and Grashuis, 2021).

While few previous studies have been concerned with the farmer view of cooperatives as a tool for environmental protection, there is much research on farmer motivation for environmental practices in their own agricultural operations (Lokhorst et al., 2011; Lokhorst et al., 2014; Mills et al., 2017). This research indicates that many farmers reduce the use of chemicals on their own initiative. Care for the environment may fit a farmer's self-identity and is often related to social norms (Van Dijk et al., 2016).

However, the environmental actions of individual farmers have only moderate effects because each farmer's acreage is smaller than the habitats of many species of wild animals and plants, and small fields increase the risk for the leakage of pesticides, weeds, polluted water, etc. Therefore, better environmental protection is achieved if several neighboring farmers take part in environmental programs (Emery and Franks, 2012; McKenzie et al., 2013). This objective can be attained with the help of local cooperatives where the members live close to one another.

Cooperative member democracy may be effective in coordinating member incentives to conduct environment-friendly production (Morfi et al., 2015; Yu and Nilsson, 2018). With the help of its financial and social capital, a cooperative can include environmental issues beyond the marketing of member products, the sales of farm inputs to members or other tasks. Fahlbeck and Nilsson (2002) have presented an example where an existing cooperative established a new line of organic dairy products after a group of farmers convinced fellow members to do so.

A cooperative could orient itself toward environmental production for economic reasons. The farmers may realize that the excessive use of chemicals is unnecessarily costly, and it may harm the long-term fertility of the soil to the detriment of future generations. Moreover, if there is a strong demand for environment-friendly products, a higher price may outweigh the higher cost of environmental production.

In some European countries, governments have contracts with cooperatives, whereby the farmers receive remuneration for specific protection measures. Nevertheless, the environmental work is often driven by farmer idealism and their connection to nature (Lokhorst et al., 2011). This is also true in China; some cooperatives receive financial support for environment-friendly production. In recent years, the environmental protection awareness of Chinese farmers has increased, especially after the publicity of China's green policy. Yu and Huang (2020) have demonstrated that Chinese cooperatives also provide noneconomic benefits to their members. Cooperatives strengthen their members in social and environmental respects. Cooperatives pay attention to a

TABLE 1 | Dependent and independent variables and descriptive statistics for the models.

Variable	Symbol	Measurement and evaluation	Mean	Std. Dev.	Min	Max
Dependent variable	Y	After joining the cooperative, I became more satisfied with my life. (1 = yes; 0 = no)	0.787	0.411	0	1
Economic dimension	EC	(1) Joining the cooperative has improved my standard of living.[a]	3.976	0.573	2	5
Social dimension	SO_1	(2) After joining the cooperative, I communicate more with other villagers.[a]	3.981	0.617	2	5
	SO_2	(3) After joining the cooperative, I know more about democracy and unity.[a]	3.953	0.646	2	5
Environmental dimension	EN_1	(4) My cooperative plays an obvious role in promoting the improvement of the local environment such as soil protection.[a]	4.009	0.851	2	5
	EN_2	(5) After joining the cooperative, I have adopted pro-environment production practices.[b]	3.806	0.876	1	5
Control variables	X_1	(6) What is the equity capital of your cooperative? (10 thousands of yuan)	480.418	563.162	10	4.180
	X_2	(7) What was your cooperative's sales volume (million yuan) last year? (1 = no more than 100; 2 = 100–500; 3 = 500–1,000; 4 = 1,000–5,000; and 5 = more than 5,000)	2.602	1.408	1.000	5.000
	X_3	(8) What is your educational level? (1 = college or above; 2 = senior high school or similar; 3 = junior high school; and 4 = primary school or below)	2.237	0.947	1.000	4.000
	X_4	(9) What is your age? (years)	50.085	9.596	25.000	70.000

[a]*The options for questions (1) to (4) are as follows: 1 = strongly disagree, 2 = disagree, 3 = neither agree nor disagree, 4 = agree, and 5 = strongly agree.*

[b]*The pro-environmental behaviors include the following five practice: organic fertilizer application technology, straw returning technology, green prevention and control of crop diseases and insect pests, less times of spraying pesticides in the same scale planting than in the past, and production of organic fertilizer from livestock manure. The options for question (5) are as follows: 1 = none of the above pro-environmental behaviors are selected, 2 = one of the above options is selected, 3 = two of the above options are selected, 4 = three of the above options are selected, and 5 = four or five of the above options are selected.*

sustainable and balanced development of the economic and noneconomic interests of their members. On the other hand, Zhou et al. (2018) have reported that Chinese cooperatives recommend their members to use more chemical fertilizers and more pesticides, both of which may harm the environment, and consequently, members with large social networks will use more chemical inputs. Abebaw and Haile (2013) have reached a similar conclusion in a study of Ethiopian smallholders. These findings pertain to agriculture in less developed regions where cooperatives have the task of promoting farmers' economy.

Even though the references above provide partly contradictory findings, the overall tendency is that cooperatives may act to protect the environment. This leads to the third hypothesis:

Hypothesis 3: There is a positive relationship between Chinese farmer satisfaction with their cooperatives and their perception that the cooperatives contribute to alleviating environmental problems.

METHODOLOGY

Variables

To explore the relationship between members' satisfaction with their cooperatives and their assessment of them in economic, social, and environmental terms, data were collected through personal interviews with members of farmer cooperatives in Fujian Province. This province is located on the coast of the East China Sea and is one of the most developed provinces in China. Fujian Province has almost 40 million inhabitants, and it covers 124,000 km^2 of which 80% is mountainous and hilly.

Before the survey, the research team worked out a question guide for the dependent and independent variables. The dependent variable was farmer satisfaction with their cooperative. The respondents were asked to state whether their membership in the cooperative had made them more or less satisfied or contented, using the Chinese expression for "happy." The operationalization of this variable is shown as Y in **Table 1**.

The independent variables represent farmer views of their cooperatives in economic, social, and environmental terms. Each dimension was operationalized into one or two questions in a questionnaire. Yu and Nilsson (2018) and Feng et al. (2016) have influenced the measurements used. **Table 1** shows how the variables were measured.

The economic dimension: One question in the questionnaire concerned the respondents' opinion about whether the cooperatives improved their standard of living (EC in **Table 1**).

The social dimension: Two questions in the questionnaire represented the social dimension. One asked what the cooperative meant to members (SO_1) and the other one asked what the members did for their cooperative in terms of member democracy (SO_2).

The environmental dimension: The environmental ambitions of a cooperative may be seen at two levels: what the farmers think about the environmental work and whether they consider themselves as following the rules. Thus, in **Table 1**, EN_1 shows the question about the farmer member view concerning whether their cooperatives strive for environmental progress, and EN_2 represents whether farmers consider themselves as having adopted the cooperatives' pro-environmental production practices.

Control variables: Four control variables were selected (**Table 1**). Variable X_1 and X_2 represent two crucial attributes of the cooperative, namely, the cooperative's total amount of equity capital and its total sales volume, respectively. These factors have been demonstrated in previous research to be related to the members' perception of their cooperative (Huang et al., 2013; Yu and Nilsson, 2018; Yu and Huang, 2020. Other control variables are educational level, X_3, and age, X_4, both of which have been demonstrated to be related

TABLE 2 | Parameter estimates for the binary logit models for farmer's satisfaction and assessment of cooperative functions.

		Model 1		Model 2		Model 3		Model 4	
Variable		**Coef**	**Std. Err**	**Coef**	**Std. Err**	**Coef**	**Std. Err**	**Coef**	**Std. Err**
Standard of living	*EC*	2.133***	0.56	2.140***	0.554	2.177***	0.532	2.249***	0.521
Social communication	SO_1	3.032***	0.758	3.024***	0.753	2.791***	0.704	2.879***	0.685
Democracy and unity	SO_2	0.971*	0.568	0.983*	0.556	0.845*	0.501	0.866*	0.501
Environmental improvement	EN_1	0.789*	0.477	0.811*	0.416	0.799**	0.402	0.813**	0.396
Pro-environmental production	EN_2	0.033	0.347	/	/	/	/	/	/
Cooperative's equity capital	X_1	0.00214*	0.00113	0.00215*	0.00113	0.00208*	0.00107	0.00219**	0.00106
Cooperative's sales volume	X_2	0.164	0.247	0.164	0.247	0.122	0.241	/	/
Educational level	X_3	−0.141	0.355	−0.143	0.355	/	/	/	/
Age	X_4	0.0482	0.0313	0.0483	0.0313	/	/	/	/
	CON	−28.31***	5.183	−28.32***	5.183	−24.79***	4.205	−25.31***	4.151
Chi-square		117.960		117.950		115.300		115.030	
Log likelihood		−50.371		−50.376		−51.702		−51.835	
Pseudo R^2		0.539		0.539		0.527		0.526	
Percentage correct (%)		92.420		92.420		91.470		91.470	

****, **, and * represent significance at the 1%, 5%, and 10% levels, respectively; "/" indicates that the variable is not included in this model.*

to members' satisfaction with their cooperatives in many other studies.

Case Study Area and Field Survey

Farmer cooperatives in China aim to provide benefits to farmers through services that encourage the adoption of new agricultural technologies, sustain farming practices, and market agricultural products (Ma et al., 2018). This is also true for Fujian Province. Fujian's forest coverage rate is as high as 66.80%, ranking first in China for 40 consecutive years. In 2016, the State Council issued the implementation plan for the National Ecological Civilization Experimental Zone (Fujian), which identified Fujian as the first National Ecological Civilization Experimental Zone in China, exploring experience and providing demonstration for the national ecological civilization system construction. According to the statistics of the agricultural department, by the end of 2018, Fujian had taken the lead in advocating that tea plantations should not use chemical pesticides. Compared with 2016, the use of chemical fertilizers and pesticides decreased by 9.1 and 10.3%, respectively, and the comprehensive utilization rate of livestock and poultry manure was 80%. The green development of agriculture achieved a new breakthrough. Farmers' cooperatives in Fujian not only serve as a channel to help farmers or the rural poor enlarge or improve operations, financing assistance etc., to increase farmers' income and enhance their welfare but also play an active role in guiding farmers to adopt pro-environment production technology, thus promoting the development of green agriculture production. Personal interviews were conducted with 211 members of 63 cooperatives in Fujian Province, all of them having operations. The data collection took place in the period from July 2019 to July 2020. The sampling was conducted in three stages to identify the respondents: geographical locations, cooperatives, and individuals. First, five prefecture-level cities were selected on the basis of their geographical location (Xiameng, Ningde, Putian, Sanming, and Longyan). Second, a number of cooperatives were selected from among the 28 cooperatives in the eastern part of Fujian Province and the 37 in the western part. A few were excluded because they had members who did not participate in agricultural production. Thus, 63 cooperatives were selected, of which 53 (84%) were fruit and vegetable cooperatives and 10 (16%) were aquaculture and livestock cooperatives. These figures are close to 82 and 18%, respectively, of that which the agricultural department of the provincial government reported for all cooperatives who have participated in agricultural production in the province since 2017.

In the third stage of the sampling procedure, two to six members were randomly selected from each cooperative, resulting in 211 respondents, of whom 66 were core members and 145 were common members. To make the sample more representative, both chairpersons and other members were interviewed. The research team got in touch with the directors of the cooperatives based on the contact information provided by the government's local agricultural departments. The directors were asked to provide contact information for about 5% of its members, and the research team interviewed those members, although some members refused to be interviewed.

It appeared that the sample has a similar spread in terms of geographical distribution, production orientation, and membership type. As shown in **Table 1**, the average age of the respondents was approximately 50 years. About two-thirds (68%) of the respondents had an educational level equivalent to having completed junior high school. On an average, the respondents owned shares in their cooperatives to an amount of 4,800,000 yuan. Close to two-thirds of the respondents (61%) received an income from the cooperatives that was less than 5 million yuan per year, which indicates that most of them were small-scale producers (100 yuan is 15 U.S. dollars or 12.80 euro).

The Logit Model

The data were analyzed using logit regression. It has been widely used in studies on cooperatives (Guo et al., 2011; Yu, 2012; Kontogeorgos et al., 2014; Feng et al., 2016). A logistic regression model is specifically designed to analyze the relationship between the binary dependent variable and a set of explanatory variables (Stock and Watson, 2014). In this study, the explanatory variables were designed according to economic,

TABLE 3 | Average marginal effects of variables in logit Models 1 and 4 of member satisfaction.

Variable		Marginal effect in Model 1		Marginal effect in Model 4	
		dy/dx	Std. Err	dy/dx	Std. Err
Standard of living	EC	0.154***	0.033	0.166***	0.030
Social communication	SO_1	0.219***	0.045	0.213***	0.040
Democracy and unity	SO_2	0.070*	0.041	0.064*	0.036
Environmental improvement	EN_1	0.057*	0.034	0.060**	0.028
Pro-environmental production	EN_2	0.002	0.025	–	–
Cooperative's equity capital	X_1	0.000*	0.000	0.0001**	0.000
Cooperative's sales volume	X_2	0.012	0.018	–	–
Educational level	X_3	–0.010	0.026	–	–
Age	X_4	0.003	0.002	–	–

****, **, and * represent significance at the 1%, 5%, and 10% levels, respectively.*

social, and environmental features. The binary logit models pertaining to the hypotheses are

$$\operatorname{logit}(p_i) = \log\left[\frac{p_i}{1-p_i}\right] = \alpha_i + \beta_i EC_i + \gamma_{ij} SO_j + \delta_{im} EN_m + \theta_{ik} X_k + \varepsilon_i, \quad (1)$$

where p_i is the likelihood of member satisfaction, $p_i = P(Y_i = 1)$; EC_i represents the economic function independent variable; SO_j represents the social function independent variable $j(j = 1, 2)$; EN_m represents the environmental function independent variable $em(m = 1,2)$; and X_k represents the other independent variable $k(k = 1,\ldots,4)$.

To assess the effects of explanatory variables on the probability of member satisfaction, marginal effects were calculated as the amount of change in the probability of satisfaction as a result of one unit change in a continuous explanatory variable (or a change from "0" to "1" in a dummy variable) while holding all other explanatory variables at their means (Washington et al., 2020).

$$ME(x_i) = d\left(\frac{e^{\beta X_i}}{1+e^{\beta X_i}}\right) \Big/ dx_i, \quad (2)$$

where $ME(x_i)$ is the marginal effect of the variable x_i.

FINDINGS

Statistical Analyses

Table 2 presents the parameter estimates and presents a summary of the effect of each predictor. All hypotheses were supported by the data to some degree.

The binary logit model cannot directly reflect the degree of influence like the general regression method. It is necessary to also use the marginal effect regression based on binary logit regression to investigate the degree of the influence of the functions of cooperatives on member satisfaction. **Table 3** reflect the average marginal effects.

In order to test whether the above model results were robust, we used the dependent variable w (Are you satisfied with the service provided by the cooperative? 1 = yes; no = 0). The results are shown in **Table 4**.

Economic Dimension of Member Satisfaction

Table 2 shows a positive and strongly significant relationship between member satisfaction with their cooperatives and member assessment of their living standard. This finding supports Hypothesis 1: *The more the farmers felt satisfaction after joining their cooperatives the more they perceive that the cooperatives contribute to a higher standard of living.* The regression in **Table 4** also supports this finding. According to the marginal effects in **Table 3**, members with a better economy had a 16.6% higher probability of satisfaction.

This finding is in accordance with what could be expected from a theoretical point of view (Ollila, 1994; Hendrikse and Veerman, 2001; Feng and Hendrikse, 2008). Small-scale farmers receive economic benefits through cooperative activities (Feng et al., 2016). The findings are also in line with empirical studies with a focus on the income levels and memberships of smallholders in Mesoamerica (Hellin et al., 2009), Ethiopia (Bernard and Spielman, 2009), China (Ito et al., 2012; Jia et al., 2012; Ma and Abdulai, 2016), and Ruanda (Verhofstadt and Maertens, 2014).

In addition, in the past few years, Chinese farmer cooperatives have become an important way for farmers to get out of poverty. In our field investigation, many farmers said that due to the cooperatives, their income has been greatly improved, and they are satisfied and grateful for the help from the cooperatives.

TABLE 4 | Balance test.

Variable		Coef.	Std. Err
Standard of living	EC	0.726*	0.394
Social communication	SO_1	0.977*	0.534
Democracy and unity	SO_2	0.615	0.530
Environmental improvement	EN	1.204***	0.401
Cooperative's equity capital	X_3	0.001*	0.001
	CON	–11.964***	2.752
Chi-square	56.44		
Log likelihood	–59.837		
Pseudo R^2	0.3205		

****, **, and * represent significance at the 1%, 5%, and 10% levels, respectively.*

Social Dimension of Member Satisfaction

As shown in **Table 4**, the coefficients of SO_1 were significant in all models even at the 1% level, that is, social communication predicted member satisfaction in all models. The other social variable, SO_2, was positively related to satisfaction in all models at the 10% level. The alternative satisfaction regression in **Table 4** presents almost the same finding. The results in **Table 3** also show that members with an enhanced social embeddedness had a 21.3% higher probability of being more satisfied with the cooperatives. Members who raise the awareness of democracy and unity have a 6.4% higher probability of being satisfied with their cooperative. According to our statistics, the percentage (95.2%) of farmers who confirm satisfaction showed a SO_1 level of between 4 and 5, whereas only 37.4% of the farmers who are not satisfied showed a SO_1 level of between 4 and 5. The distribution of SO_2 shows a similar pattern: 92.8% of the farmers who were satisfied chose a level of SO_2 between 4 and 5, while only 44.4% of the farmer in the other group chose a level of SO_2 between 4 and 5. Hypothesis 2 is supported overall: *There is a positive relationship between Chinese farmer satisfaction with their cooperatives and the member perception that the cooperatives contribute to their social life.*

This finding can be viewed in light of the development in the Chinese countryside. The traditional rural social networks and rural community are threatened by the outflow of the rural population. Farmers are forced into the market economy and urban multiculturalism. Cooperative participation generates social trust, but it also makes members focus on commitment. (Valentinov, 2004a, b; Nilsson et al., 2009; Yu and Nilsson, 2019). Diener and Biswas-Diener (2002) suggest that social connections make poor people more satisfied with life, while higher incomes do not always mean more satisfaction. After joining a cooperative, members communicate more with others, which is conducive to getting useful production technology while also reducing loneliness, relieving anxiety, and otherwise improving social conditions. Moreover, many farmers have increased their sense of democracy and unity, which is positively related to their satisfaction.

Environmental Dimension of Member Satisfaction

In all models, there is a significantly positive relationship between the member assessments of a cooperative's environmental work and their satisfaction with their cooperative (**Tables 2–4**). In the alternative regression in **Table 4**, the cooperative's environmental dimension positively correlates with member satisfaction with their cooperatives. This finding partly supports Hypothesis 3: *There is a positive relationship between Chinese farmer satisfaction with their cooperatives and their perception that the cooperatives contribute to alleviating environmental problems.* According to the marginal effects in **Table 3**, members who feel that their cooperative plays an important role in environmental improvement such as soil amelioration have a 6% higher probability of satisfaction.

The other environment variable (EN_2) shows no significant relation with members' satisfaction. Nevertheless, the cooperative may promote members' pro-environmental behavior because in a longer time perspective, more members may be willing to abide to the cooperatives' guidelines, which also tend to become stricter because of the government's increasingly high requirements for environmental protection (Yuan et al., 2020).

Some previous studies have found that the existence of cooperatives is negatively related to various agricultural practices, among them the use of chemicals (Abebaw and Haile, 2013). In line with Ma et al. (2018), cooperatives may improve smallholder agricultural performance through services that enhance the adoption of new agricultural technologies and sustainable farm practices, which include pro-environment production practices.

CONCLUSIONS

This study is based on data collected in 2019 and 2020 through personal interviews with a randomly selected sample of 211 members of 63 cooperatives in Fujian Province of China. The findings indicate that member satisfaction with their cooperatives is related not only to member assessments of their cooperatives' provision of economic and social benefits but also to their perception of their cooperatives' environmental work.

To check the validity of this relationship further, we ran a logit model for selection equation through a dependent variable of satisfaction with the cooperatives' services and independent variables in economic, social, and environmental dimensions. The regressions showed that the variables were significant, suggesting high validity of the results.

While previous studies have concluded that smallholders appreciate their cooperatives in economic and social terms, this study is the first to identify a positive relationship between the environmental performance of the cooperatives and member satisfaction with their cooperatives. Consequently, this study indicates that at least under certain circumstances, the environmental actions of cooperatives may be related to member satisfaction with their cooperatives.

There is no basis to tell whether the findings are representative for other regions of China or elsewhere, neither to tell whether the findings will persist nor change over time. It is, however, not likely that the members' view of their cooperatives' environmental policies will become much different because the policies are decided upon by the members themselves. Because of the social capital within the membership, it is not likely that one member category will challenge another member category by introducing very different environmental rules.

The study had some limitations. One caveat is that the respondents may have had limited knowledge about the actual environmental performance of their cooperatives. There might be a membership norm that the environmental protection should be regarded positively. Moreover, the respondents might have answered positively because they were positive to their cooperatives in economic and social terms. It is understandable that the respondents are positive to environmental actions if these lead to economic benefits. It is possible that the cooperatives have not taken much environmental action, but that leadership has talked about it, and the leadership wants to communicate about environmental efforts in positive terms.

Even though farmer cooperatives can play a role in environmental protection, their contribution is limited. Cooperatives cannot solve environmental problems beyond their operational area and outside member agricultural practices. Other institutional arrangements are necessary to solve other problems, primarily governmental ones. Cooperatives may help governments to implement environmental policies. Similar to the European experience, the government could provide financial support to cooperatives and their members to protect the environment. Many European farmers are positive toward governmental support for environmental protection.

Furthermore, agricultural cooperatives with a pro-environmental policy may have a pilot and demonstration effect, thereby stimulating others to take up the challenge. One condition for this to happen is that the cooperatives have both good financial records and satisfied members. Another condition is information dissemination about these facts and the cooperatives' planting and breeding modes, possibly mediated by government. If other cooperatives follow suit, there is a chance for rising consumer awareness and the development of less costly inputs, whereby more environmentally friendly farming practices may evolve in China.

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. The participants provided their informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

LY: conceptualization, data collection, wrote background, data description, methodology, and explanation of results. JN: concept development, analysis, writing, reviewing, and editing. Both authors contributed to the article and approved the submitted version.

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Restoring Nature at Lower Food Production Costs

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Growing competition for land, water and energy call for global strategies ensuring affordable food production at minimum environmental impacts. Economic modelling studies suggest trade-off relationships between environmental sustainability and food prices. However, evidence based on empirical cost-functions supporting such trade-offs remains scarce at the global level. Here, based on cost engineering modelling, we show that optimised spatial allocation of 10 major crops, would reduce current costs of agricultural production by approximately 40% while improving environmental performance. Although production inputs per unit of output increase at local scales, a reduction of cultivated land of 50% overcompensates the slightly higher field-scale costs enabling improved overall cost-effectiveness. Our results suggest that long-run food prices are bound to continue to decrease under strong environmental policies. Policies supporting sustainability transitions in the land sector should focus on managing local barriers to the implementation of high-yield regenerative agricultural practices delivering multiple regional and global public goods.

Keywords: cropland expansion, food security, yield gaps, land sparing, food supply, global economic assessment, optimised land use, cost engineering framework

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INTRODUCTION

Increasing competing demands for land, water and energy (Steffen et al., 2015) along with increasing world population call for strategies to minimise environmental impacts while producing adequate food for 10 billion people (United Nations, 2017; Ramankutty et al., 2018). The Sustainable Development Goals (SDGs) agenda of the United Nations articulates conditions for the sustainable management of these challenges, through the environmental sustainability pillar and SDG-2, that aims to achieve food security and promote sustainable agriculture (UN, 2015)–objectives vital to the success of the entire agenda (FAO, 2016a). In this context, SDG-2 targets "doubling agricultural productivity" (Target 2.3), yet this is not globally applicable as in different regions, with certain yield limitations (Tumushabe, 2018), this would contrast the goal of sustainable agriculture (Gil et al., 2019). In this context, the debate of land sparing vs. land sharing has emerged assessing balances between environmental conservation and agricultural yields (Lamb et al., 2016). Land sparing entails setting aside land utilised for high-yield agricultural production on a small land footprint to allow for biodiversity conservation on non-agricultural land (Balmford et al., 2015; Kremen, 2015; Phalan, 2018). On the contrary, land sharing advocates integration of environmental conservation and food production incentives on the same plots of land through low-intensity systems on a larger land footprint (Kremen, 2015). In the present analysis, agricultural intensification exceeds the traditional perspective of high-yield farming resulting from high-input high-output relationships but rather, is reconciled with natural restoration though spatially optimised land-sparing that enables closing current "yield gaps" (the difference between observed and attainable yields in a given location) (Grassini et al., 2015).

The land sparing-sharing model has received both positive and criticizing reviews (Phalan, 2018). Criticism in land sparing stems from the intensive use of agricultural land that is required to achieve high yields (Law and Wilson, 2015) which has led to the development of arguments suggesting trade-off relationships between productivity and socioeconomic goals (Kremen, 2015; Frison, 2016; Mehrabi et al., 2018), productivity and environmental conservation (Lamb et al., 2016) or the necessity of demand-side adjustments to meet environmental and food security goals (Erb et al., 2016). Kremen (2015), points out that sustainable intensification provides the means to spare land in a capital- and input-intensive way which fails to address global hunger due to the existing inequalities in resource distribution. Egli et al. (2018), suggest that the high-input agriculture associated with attempts to close yield-gaps on existing croplands and increase food security, negatively affect multiple dimensions of biodiversity. On the contrary, research has shown that land sparing can resolve such trade-offs by producing adequate volumes of food and also by improving environmental performance of agricultural production, through yield gaps closure that results in reduced emissions, irrigation and fertilisation (Cannon et al., 2019; Feniuk et al., 2019). The added value of the land sparing concept has resulted in the development of incentives providing evidence in production practices that reduce emissions (Folberth et al., 2020) and generate cost-effective solutions (Desquilbet et al., 2017). Recent studies have highlighted the importance of integrated approaches studying policies for land sparing taking into consideration economic mechanisms and feasibility (Lamb et al., 2016; Salles et al., 2017) yet, agricultural production costs in the land sparing context have been overlooked by the literature.

Due to its links with environmental and food security objectives, the global agricultural transition in cost-effective production systems is a great planetary challenge. As economics drive agricultural systems decisions (Marinoni et al., 2012), policy solutions will need to analyze the quantitative relationships between food production goals, environmental targets and agricultural production costs on which we focus in this paper. Here we provide an initial and fundamental estimation of the global costs of agricultural production to test the basic hypothesis that production of current food baskets at global scales is less costly in land-sparing scenarios than in present conventional production practices. We accomplish that by comparing actual business-as-usual plans including current cropland allocation and production practices (BAU) to land sparing strategies designed to minimise cropland expansion by approximately 50% of the current cropland extent while maintaining present food production volumes (MLS and TLS). We conduct financial estimations at sub-national scales (in varying spatial simulation units of ~ 9.26 km × ~ 9.26 km–~ 55.56 km × ~ 55.56 km, see Methods) that were aggregated to estimate national and global costs of agricultural production (**Figure 1**). While the focus of the present analysis was to investigate cost functions in agricultural production under current and two land sparing production scenarios, we also quantified crop-specific food supply implications through metrics that include global supply curves as well as costs of energetic values per unit of output across the three scenarios. The estimation of financial implications of land sparing production scenarios is based on hypothetical crop land use allocation while implementation barriers such as transaction costs, lack of access to knowledge and best available technologies are left aside. Our results, nonetheless, deliver insights, addressing policy makers, on systems cost functions under land-sparing targets. This novel effort to synthesise cost implications on agriculture at global scales, provides direct information on cost-competitiveness of alternative production scenarios thus, highlights their financial attractiveness–knowledge critical to the development of policies designing the ways in which food production systems could evolve and be managed in the future.

We seek to contribute to the examination of the longstanding hypothesis that trade-off relationships link agricultural productivity and environmental performance as well as agricultural productivity and social (food security) and economic (cost effectiveness) objectives suggesting whether this hypothesis can be rejected at a global scale. We apply a novel bottom-up cost engineering assessment at sub-national scales for 154 countries to provide crop-specific information on cost-effectiveness gains from two land-sparing case study production scenarios for the production of ten major crops that include barley, groundnut, maize, potato, sugar beet, rice, sunflower, sorghum, soybean and wheat (**Supplementary Table S1**). The ten crops considered herein provided 52% of total direct human calorie intake and 63% of plant-based direct human calorie intake in the year 2015 (FAO, 2016b). Evaluating the potential of current global agricultural systems to adapt land-sparing strategies provides insights about reductions in production costs and land requirements for the supply of sufficient food while addressing environmental performance objectives. The global perspective of the analysis enables us to identify broad trends of cost-effectiveness and spared cropland while the sub-national cost accounting capabilities of our framework allow the identification of increased cost patterns at the field scale, as a result of production intensity. In turn, this provides critical inputs to national research priorities that seek to evaluate the cost-competitiveness of such strategies across different crops, cropping systems and locations to promote their implementation.

This paper has five sections. Section "***Introduction***" provides an overview of land-sparing as a strategy to reach environmental and food security SDGs and briefly introduces the main methodological steps followed in this assessment. Section "***Literature review on land-sparing trade-offs and production costs***" discusses previous research on land-sparing and highlights the research gaps identified and aimed to be addressed in the present analysis. Section "***Methods***" describes in detail the study design, cost engineering framework as well as physical and financial modelling set up. In the next section, "***Results***" we

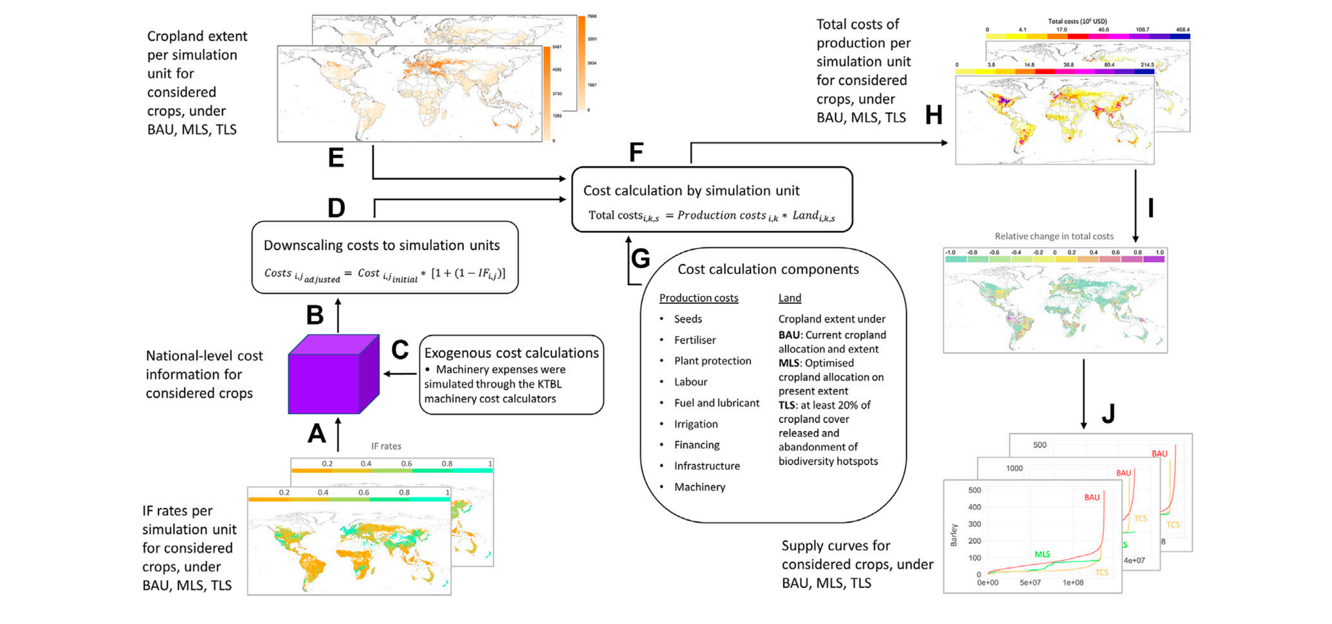

FIGURE 1 | Schematic design of the study, **(A–J)**. Intensification factor (***IF***) rates **(A)** were calculated introducing input-output relationships at a simulation unit basis using physical information on current and attainable yields and corresponding nutrient requirements derived from SPAM 2010 v1.1 (47) (this data was scaled up and to match food production volumes during the reference period of 2011–2015 using FAOSTAT reported values on production of the ten crops considered) and the EPIC-IIASA global gridded crop model, respectively. ***IF*** rates are combined with national-level cost information **(B)** and the exogenously simulated (through KTBL plant process cost calculators) machinery expenses **(C)** to downscale costs at subnational scales, in a simulation unit basis **(D)**. Cropland extent **(E)** for the considered crops in BAU was obtained from SPAM 2010 v1.1 (similarly to yields, data was scaled up to match food production volumes around the baseline year) while in MLS and TLS cropland was derived from Folberth et al.'s optimised land-use datasets. Physical and financial information covering nine cost elements for the three examined production scenarios **(G)** is combined in the cost calculation function **(F)**. Costs are then aggregated to total costs for all crops per scenario **(H)** to assess cost effectiveness at global scales and also evaluate relative change in total costs at a simulation unit spatial resolution **(I)**. Finally, relationships between global food production and associated costs of production by crop commodity and production scenario are evaluated in the context of global food supply curves **(J)**.

analyze global agricultural production costs and present the main findings in the context of cost effectiveness gains between different production scenarios, the spatial distribution of costs and the global food supply implications. Finally, Section "***Discussion and conclusion***" concludes with main lessons from the cost implications of the case study land-sparing strategies.

LITERATURE REVIEW ON LAND-SPARING TRADE-OFFS AND PRODUCTION COSTS

Global-scale studies on land-sparing were sparked around 1996 (Waggoner, 1996) and have ever since examined the environmental and economic responses of agricultural production systems from different production strategies aiming to produce given amounts of food with least harm to biodiversity. Recent empirical evidence from Balmford et al. (2015), Finch et al. (2019), suggest that high-yield agricultural production separated from conservation of nonfarm ecosystems (land-sparing) has greater potentials than wildlife-friendly farming over expanded areas (land-sharing) to limit the ecological cost emerging from the production of food. Cannon et al. (2019), investigate ecological implications of competing land-use strategies and find that land-sparing agriculture conserves great functional diversity of species supplying key ecological functions. However, several approaches have identified a number of substantive concerns for biodiversity conservation, associated with the high intensity and specialisation of production on the parts of land that are being devoted for food production (Emmerson et al., 2016; Landis, 2017; Egli et al., 2018). Along these lines, Kremen and Merenlender (2018), suggest that we must join biodiversity conservation objectives into the landscapes we use in order to avoid mass extinction and ecosystem destruction. In this context, Grass et al. (2019) highlight that such solutions are not mutually exclusive, as both are required to harmonise management choices for the multifunctionality of agricultural landscapes (Seppelt et al., 2016).

Phalan, (2018) reviews the conceptual and analytical strengths of the land sparing-sharing framework suggesting that while it is a model of biophysical, and not economic relationships, it provides a method to produce economic measures such as opportunity costs. To that end, Zabel et al. (2019), examine the implications of cropland expansion and agricultural intensification as ways to respond to the increasing demand patterns and find that while both would negatively affect biodiversity, increased food production will reduce crop prices under these scenarios. Pannell et al. (2014), investigate the economics of land conservation approaches, as strategies that address food security and land degradation, identifying the economic drivers that have been influencing the adoption of conservation agriculture practices. Runting et al. (2019), explore economic returns in wood products under land sparing-sharing strategies and best practice implementation in tropical forests suggesting that sparing provides better environmental benefits than sharing and also leads in lower costs than in better management.

Although the literature provides an extensive discussion of the relationships between productivity and biodiversity in the context of land restoration, it rarely examines the economic implications triggered by such production alternatives through analytical methods (Ephraim et al., 2016). Owing to the systems inherent complexity but also lack of consistent and adequate crop-specific financial information at global scales, to the extent of our knowledge, there are no analytical approaches investigating crop-specific and spatially explicit global-scale costs of production under existing and land-sparing production scenarios. The latter emerges as a significant research gap because it is necessary to evaluate the crop- and location-specific financial attractiveness of sustainable practices (Piñeiro et al., 2020) as higher costs essentially trigger higher risk to farmer livelihoods, and this is one of the aspects that we aim to improve alongside food security and environmental sustainability. Providing such an analytical framework, addresses this need for knowledge which is essential for investigating the cost-competitiveness of different agricultural production strategies.

MATERIAL AND METHODS

Study Design and Intensification Scenarios for Land Sparing

The study investigated the implications on costing mechanisms within agricultural production on the basis of land-sparing production scenarios. We conducted an engineering cost assessment over current practices to compare them with land sparing strategies. To achieve that, we developed the present global costing framework in such way that has the capacity to assess cost-effectiveness in the land sparing scenarios under consideration.

Here we develop a cost accounting method to investigate potential cost-effectiveness in land sparing production scenarios. We estimate costs for three production scenarios namely, i) actual business-as-usual plans including current cropland allocation and production practices (BAU), ii) maximum land sparing (MLS) where cropland extent is optimised allowing the entire present cropland in each simulation unit or pixel to remain occupied after crop reallocation if it is a solution of the optimisation and iii) targeted land sparing (TLS) where cropland extent has been optimised with an enforced uniform release of at least 20% of cropland cover in each simulation unit or pixel and the abandonment of biodiversity hotspots by simultaneously achieving attainable yields of 10 major crop commodities (optimisation modelling developed by Folberth et al., 2020). The optimisation method modelled spatial allocation of agricultural systems at global scales while maintaining crop-specific production volumes reported by FAO for the years of 2011–2015 (FAO, 2016b). In this study MLS represents a reference point of what degree of land sparing scenarios are technically feasible given attainable yields and current agricultural technologies. Additionally, TLS provides a reference point for a global scenario combining habitat restoration of threatened species and introducing systematically distributed landscape slots as wildlife habitats (Feniuk et al., 2019) or zones to compensate for negative impacts of intensive agriculture (Schulte et al., 2017).

The harvested area of the ten crops considered encompasses presently 62% of total cropland. Several of these crops play an important role in livestock feed supply (FAO, 2016b). However, this is challenging to fully quantify at global scales as crop uses are reported in FAOSTAT only for the primary step, which is in the case of feed stuffs in some cases processing. To provide an overview of major uses for the crops selected for this study, we compiled major crop uses in **Supplementary Table S2**.

Cost Accounting Modelling Set Up

This method enables geographically explicit calculation of agricultural production costs for the various crop commodities and management methods. To simulate production costs, our framework includes direct (variable) and indirect (overhead) costs of production. A full list of costing elements and disaggregated items is presented in **Supplementary Table S3** Production costs (per hectare) and total costs of production for cell i and crop k were calculated using the basic forms:

$$\text{Production costs}_{i,k} = SDC_{i,k} + TFRC_{i,k} + PPC_{i,k} + TLAC_{i,k} + TFLC_{i,k} + TFIN_{i,k} + TMAC_{i,k} + INFC_{i,k} \quad (1)$$

and,

$$Total\ costs_{i,k,s} = Production\ costs_{i,k} * Land_{i,k,s} \quad (2)$$

Where $SDC_{i,k}$ represents costs for seeds, $TFRC_{i,k}$ total costs for fertiliser, $PPC_{i,k}$ plant protection, $TLAC_{i,k}$ total costs for labor, $TFLC_{i,k}$ fuel and power costs, $TFIN_{i,k}$ financing costs $INFC_{i,k}$ costs for infrastructure, $TMAC_{i,k}$ machinery expenses and $Land_{i,k}$ is number of hectares in cell i, crop k and production scenario s.

Physical and Financial Data

To estimate cost functions, we look at the intersection of biophysical and economic functions (**Figure 1**) This analysis integrates current knowledge of high-yield farming and optimised land use strategies to estimate the economic consequences of changes in global agricultural production resulting from the two land use scenarios. For physical information, current yields and harvested area were derived from SPAM 2010 v1.1 (International Food Policy Research Institute, 2019) this data was scaled up and to match food production volumes during the reference period (2011–2015) using FAO reported values on production of the ten crops. Attainable yields and corresponding nutrient requirements were derived from the established global gridded crop model EPIC-IIASA (Balkovič et al., 2014). Information was derived explicitly for sub-national grid cells that vary in sizes of ~

9.26 km × ~ 9.26 km–~ 55.56 km × ~ 55.56 km (5′ × 5′ to 30′ × 30′ arc minutes at the equator). This grid reference is a result of EPIC-IIASA integrating the process-based agronomic model 'Environmental Policy Integrated Climate (Williams et al., 1989; Izaurralde et al., 2006) (EPIC) to a global data infrastructure referenced at 5′ x 5′ spatial resolution. These five arcmin grid cells belong to the same topography classes, have identical soil texture and are located within the same 30′ x 30′ climate grid and administrative region cells that were then aggregated to simulations units. As a result, we have approximately 120,000 simulation units in varying sizes corresponding to surface areas from ~ 69 to ~ 2,500 km^2 near the equator conditional to input data heterogeneity.

Financial information is organised in a cost engineering framework, using a bottom-up cost assessment formula that includes direct costs and overheads at the field-scale, following the cost accounting system of the Farm Accountancy Data Network (FADN)[1] and the Agri-benchmark[2] network. We compiled a novel global data set containing information on production costs (reflecting costs from the perspective of the farmer) at national scales for 10 major crops derived from agricultural data surveys and platforms, the scientific literature as well as official statistical data. In such way, we developed a baseline of countries representing a range of production practices that was used to extrapolate national-scale financial information on production costs from data-rich countries in locations where no information was available (further description on data sources for listed production costs is available in **Supplementary Tables S3, S4**). To create this baseline of countries, we introduced a classification of countries based on technological adoption per country using the global cropland field size index developed by Fritz et al. (2015). Our intuition on the latter is based on evidence suggesting a relationship between field size and technology adoption (Mittal and Mehar, 2016; Brown et al., 2018) which we tested as an assumption with the number of tractors in use per country indicator provided by FAOSTAT (**Supplementary Figure S1A**). Furthermore, to test this relationship we examined the relationship between GDP (as an indicator of incomes and expenditure on goods and services) and field sizes finding that higher GDP per capita is related to larger field sizes (**Supplementary Figure S1B**). This set of relationships has been examined by Dethier and Effenberger (2012) who find that lack of credit leads in either low technological adoption directly or in the need for a loan to withstand the initial investments. Collateral then is required for the poorer farmers and when they also lack land ownership (or own very small parts), they are restricted from taking a loan and thus, physical and economic size could then determine levels of technology adoption. Furthermore, Schimmelpfennig (2016) investigates the ways and whether farm managers decide to adopt new technologies highlighting that farm size (determined from total cropland area) is a driver influencing adoption based on the finding that farms adopting agricultural technologies tend to be of larger size than those that do not. Schimmelpfennig's study offers support to relevant approaches that similarly suggest smaller farm sizes have an inverse relationship with technological adoption (Cavallo et al., 2014; Mottaleb et al., 2016; Das V. et al., 2019).

Furthermore, we utilised the established online plant process cost calculator developed by the agricultural advisory board for engineering and building (KTBL) (KTBL, 2020) to estimate country-level and crop specific machinery expenses, based on respective technology adoption and soil properties. The online plant process cost calculator simulates costs of machinery, for a range of crops, as a function of machinery power (kW) and soil hardness (light, medium or heavy soil). Other parameters include farm size and remoteness (field-to-farm distance) that here were considered as constants for all countries and we used the standardised settings of the online calculator. Based on the assumed size to technology negative relationship, we assigned lower machinery power for smaller field sizes while information for the respective soil type and tillage resistance was derived from Fischer et al. (2012). As a result, the calculator simulated machinery costs per country and crop commodity.

Following the extrapolation, pricing information was equalised per country with the use of the purchasing power parities (PPP) indicator provided by the World Bank (World Development Indicators database, 2019a). Specifically, as shown in the basic equation bellow, cost of input i in country k is calculated using cost of input i in country j and the corresponding PPP index converting prices of goods from for country j to country k. With PPP we follow the basket-of-goods approach to equalise the purchasing power of different currencies, by removing differentiation of price levels between countries (OECD and Eurostat, 2012).

$$Cost_{i,k} = Cost_{i,j} * PPP_{j-k} \tag{3}$$

Spatial Explicit Cost Estimates and Intensification Factor

Our assessment quantified the intensity of production (Intensification Factor ratio - IF) through a basic estimation of input and output relationships which was used to scale down costing information to sub-national spatial scales. For the estimation of IF we utilised physical information on current and attainable yields (production outputs) and nutrient requirements, N and P fertiliser (production inputs). This provided country-specific gradient ratios of production intensity with which costs were adjusted assuming increasing costs for production inputs with increasing intensity of production. For each scenario, production intensity differs at sub-national scales and we assume increasing costs per hectare with increasing intensification of production per crop commodity. Thus, we introduce the intensification factor (IF) ratio, which is used to scale down national-level financial

[1]For further information on data collection methods and definitions see https://ec.europa.eu/agriculture/fadn_en

[2]For further information on data collection methods and definitions see http://www.agribenchmark.org/home.html

information to a simulation unit/subnational spatial scale. Thus, *IF* estimates look at the range of intensities through a country-specific method to create a range of relative production intensity based on which, we estimate sub-national variability in costs.

With *IF* we estimate a ratio based on input-output relationships that consider current and attainable yields as well as application of N and P fertiliser for grid cell *i* in country *j*:

$$IF_{i,j} = 0.25*\left(\frac{YLDG_i}{YLDG_{MAX_j}}+\frac{YLDG_i}{YLDG_{ATT_{MAX_j}}}+\frac{FTN_i}{FTN_{MAX_j}}+\frac{FTP_i}{FTP_{MAX_j}}\right) \quad (4)$$

Where $YLDG_i$ is yield in grid cell *i* in respective scenario and water regime (rainfed or significantly irrigated), $YLDG_{MAX_j}$ is maximum yield over all cells in country *j* in respective water regime, $YLDG_{ATT_{MAX_j}}$ is maximum attainable yield over all cells in respective water regime in country *j*, FTN_i is N fertilizer rate for cell *i* and water regime, FTN_{MAX_j} is maximum N fertilizer rate for cell *i* and water regime in country *j*, FTP_i is P fertilizer rate in cell *i* and water regime, FTP_{MAX_j} is maximum P fertilizer rate over all cells in respective water regime and country *j*. Country-level financial information is then spatially scaled-down in such way that when $IF_{i,j}$ in a particular cell exceeds a certain threshold (here $IF_{i,j} > 0.75$) then costs for cell *i*, in country *j* are adjusted upwards using the following formula:

$$Costs_{\ i,j\ adjusted} = Cost_{\ i,j\ initial} * \left[1 + \left(IF_{i,j} - 0.75\right)\right] \quad (5)$$

For production systems with *IF* estimates in a lower numeric region we assume that national-scale averages represent such systems adequately and no adjustments are made.

Moreover, even though the present study estimates production costs in such granular spatial scales, it is imperative that, in order to understand cost functions, we compare trends between total costs of different scenarios and assess cost-effectiveness among them rather than focus on absolute estimates at a simulation unit basis.

Reference Period

In this study we conduct a cost engineering assessment to increase the understating around agricultural costing mechanisms and thus, for our estimations we use prices on the basis of a uniform reference period to indicate production inputs real prices. As such, in our cost model prices on production inputs were equalised in financial contexts around the year 2000 with the use of inflation rates and specifically the consumer price index (World Bank, World Development Indicators database, 2019b). Furthermore, to allow a global assessment, a monetary consistency was of essence for which we used the purchasing power parities (PPP) metrics obtained from the World Bank (World Development Indicators database, 2019a) to transform prices from local currencies to United States dollars. Finally, to then bring cost estimates from 2000 at the food production reference period (2011–2015) we inflated prices to an average of these years. The latter enables the study to derive estimations directly for various years by inflating or deflating costs without rerunning all processing.

Model Estimations Evaluation

To assess the validity of our estimations, we cross-referenced the costs per tonne for the 10 crops to FAOSTAT reported producers' prices per tonne which are the prices at the farm gate per country and crop commodity. For each of the crop commodities we derive costs per tonne through a fraction of total costs (costs per hectare multiplied by the corresponding yield) over produced tonnes (attainable or current yield multiplied by cropland extent) and find that estimated costs per tonne are consistently bellow the reported producers' prices which assures us that our estimations follow the pattern globally and fall within expected numerical regions (**Supplementary Figure S5**).

Furthermore, we conducted cross validations on modelled technological costs as well as fertiliser costs. Specifically, we analyzed the composition of total costs by investigating cost analogues for the aforementioned elements. We are particularly interested in analogues rather than absolute costs as the purpose of this analysis is to compare cost trends between the three production scenarios and assess potential cost effectiveness between them. We do this by comparing reported and modelled cost analogues and find that for machinery expenses the extrapolation method produces an estimated analogue very close to the reported when looking at US costs of production (**Supplementary Figure S6**). Concerning fertiliser cost analogues, we cross validated modelled values with data derived from FADN on 20 EU countries. The data provided is in an aggregated farm type format covering the categories of cereals and root plants. Results of the validation demonstrate that for most of the countries the differences in cost analogues are less than 10% (**Supplementary Table S5**). Exceptions are countries of small or very small field sizes which used information from the baseline from developing countries (e.g., India, Georgia and Azerbaijan). This points out that there are intra-classes within our classification system that could be further developed in the future to increase accuracy of modelled values (i.e. field size classes break down based on regions or continent).

RESULTS

Total Costs of Production Under Business-As-Usual, Maximum Land Sparing and Targeted Land Sparing Scenarios

Our results demonstrate a clear pattern of differentiation in global production costs for crop commodities between the BAU, MLS, and TLS production scenarios (**Figure 2**) that is strongly driven by the reduction of cropland extent by 50%. Globally, we estimate that total costs of agricultural production extend to $255, $149, and $166 bn for BAU, MLS, and TLS, respectively, indicating a cost-effectiveness of ~41.3 and ~34.8% for MLS and TLS, respectively. First, a negative impact in cost-effectiveness is expected due to higher localised inputs imposed by closing yield gaps through the supply of sufficient nutrients to meet plant requirements. Particularly, in cases where production

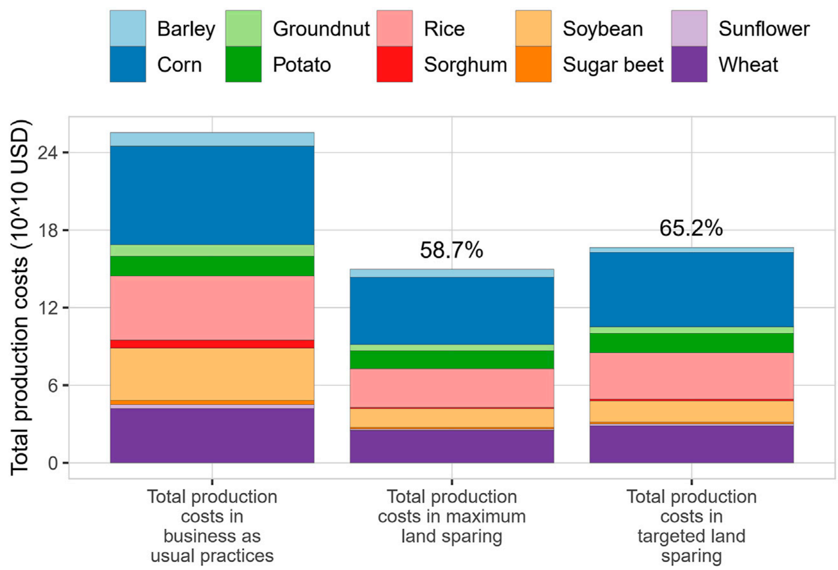

FIGURE 2 | Global costs of production in the business as usual, and the two land sparing scenarios. The stacked bars demonstrate the estimated total costs for the production of 10 major crops in actual business as usual for the reference period of 2011–2015 (left bar), estimated total costs for the production in the maximum land sparing (MLS) scenario (middle bar) and sparing of at least 20% of cropland in each simulation unit and entirely abandoning biodiversity hotspots (TLS) (right bar). On top of the middle and right bar, percentage values regard total costs of production for the 10 considered crops relative to the total costs in the business as usual scenario. In a global scale, total costs of production in BAU are approximately $255.39 bn while in the sparing scenarios costs are approximately $149.74 and $166.49 bn in MLS and TLS, respectively.

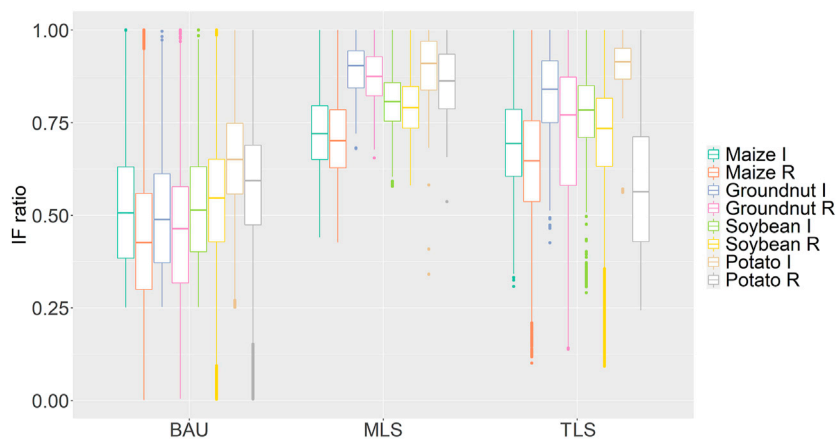

FIGURE 3 | Intensification factor per crop, simulation unit and water regime (rainfed – R and sufficiently irrigated—I) in the business as usual and the land sparing production scenarios. Boxplots display the distribution of intensity of production index (IF) in the business as usual and the two land sparing production scenarios for selected crops. Here we present IF estimates for maize, groundnut, soybean, and potato each as a representative crop, based on the FAOSTAT reported global production volumes, of the crop categories considered in this study (cereals, legumes, oil and protein crops and root vegetables, respectively). The IF index comprises of four basic components estimating intensity of production based on input (N and P fertiliser) and output (current and attainable yields) relationships (see Methods). Globally, production systems of low intensity in both MLS and TLS (***IF*** $< \sim 0.35$ and ***IF*** $< \sim 0.15$, respectively), are released, indicating that systems with low production intensity, in BAU either become more intensive or are abandoned entirely.

requires higher levels of inputs, we find that on average, costs per hectare for all crops increase by 5.3 and 4.9% globally in the MLS and TLS scenario respectively, compared to business as usual costs. Nevertheless, in particular cases, MLS and TLS production systems can be less intensive than in, business as usual due to decreased production inputs and there we observe reductions of costs per hectare by 3.7 and 3.6%, respectively, (**Figure 3** and **Supplementary Figure S3**). Such cost fluctuations are expected as we observe that the optimisation of cropland allocation shifted the intensity of production, and in particular, production systems

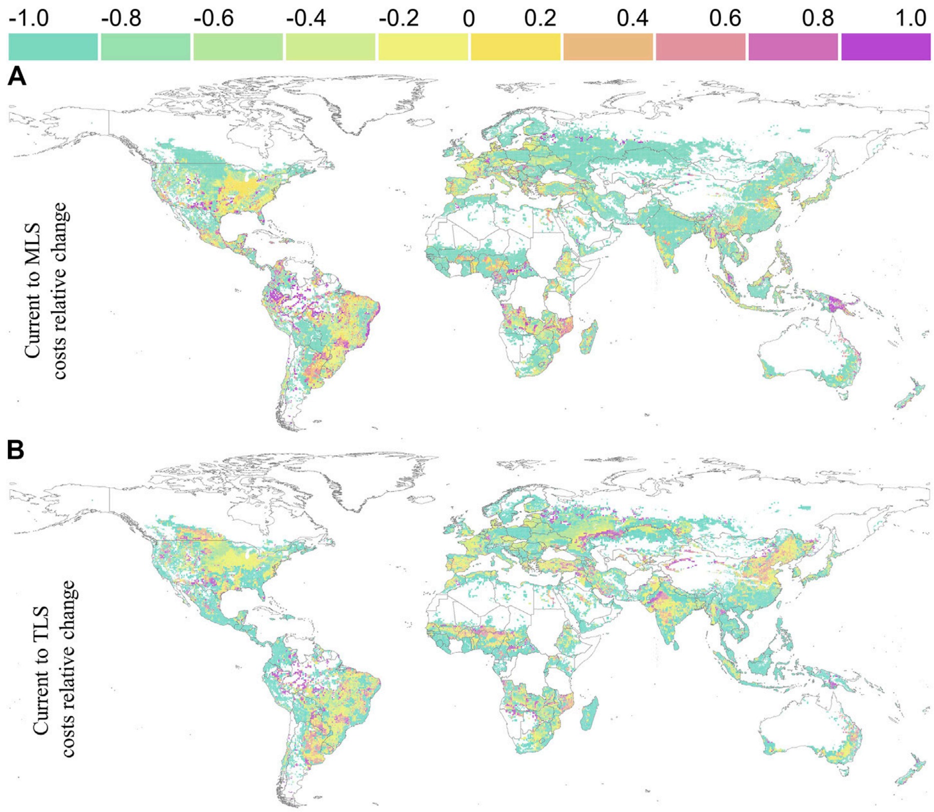

FIGURE 4 | Relative change in total costs of agricultural production for the ten major crops. **(A)**. Relative change in costs between current production costs and costs under the maximum land sparing production scenario (MLS) **(B)**. Relative change in costs between current production costs and costs under sparing of at least 20% of cropland in each simulation unit and entirely abandoning biodiversity hotspots (TLS).

are generally more intensive in MLS than in BAU and TLS (**Figure 3**; **Supplementary Figure S2**).

Second, the spatial occurrence of cropland use in MLS and to a lesser extent TLS is more prominent in regions with more favourable agroclimatic conditions, and thus, higher attainable yields, for each of the examined crops (Folberth et al., 2020). Thus, we observe that global scale ($n = 1$) vs. country scale ($n = 154$) comparisons of total agricultural costs reveal variations across scenarios not necessarily consistent to the global pattern, as intensification is taking place. More specifically, we find that ~12 and ~9% of the countries, have higher total costs in MLS and TLS, respectively, than in BAU due to higher concentration of cropland in the land sparing scenarios. In terms of the geographical distribution, in MLS, ~ 25% of these countries are in Africa, ~45% in South America, ~ 5% in Asia and ~ 25% in Europe, while in TLS ~ 55% of these countries are in Africa, ~20% in South America, ~ 20% in Asia and ~ 5% in Europe.

Mapping Total Agricultural Costs

Regions with significant reductions in total costs of production in MLS compared to BAU (**Figure 4A**) include areas with unfavourable biophysical properties such as the West coast of the United States and parts of central Asia but also in more productive regions including South Asia and South Russia. Likewise, in MLS globally, costs remain high in the areas of Central North America, East Latin America, North West Europe and some parts of South Asia. In TLS, the geographical distribution of cropland spans more widely and thus, we observe a similar pattern to the cost distribution of MLS with the addition of concentration of higher costs in Northern North America, West Europe and a significant spatial expansion of production-cost hotspots in South Asia (**Figure 4B**). Collectively, on a simulation unit basis and across the three scenarios we observe that total production costs in BAU extend to a smaller scale but to a significantly larger geographical extent. MLS and TLS estimate increased local costs compared to BAU due to higher intensity of production but in smaller land extent that ultimately results in greater cost effectiveness at global scales (**Supplementary Figure S4**).

Global Food Supply Implications

Herein we investigate the implications on food supply at a global scale and also assess cost fluctuations between the three production scenarios BAU, MLS, and TLS (**Figure 5**). We find that while the magnitude of food baskets remains the same across the scenarios, total costs of production per tonne and crop commodity is consistently lower in the land sparing scenarios

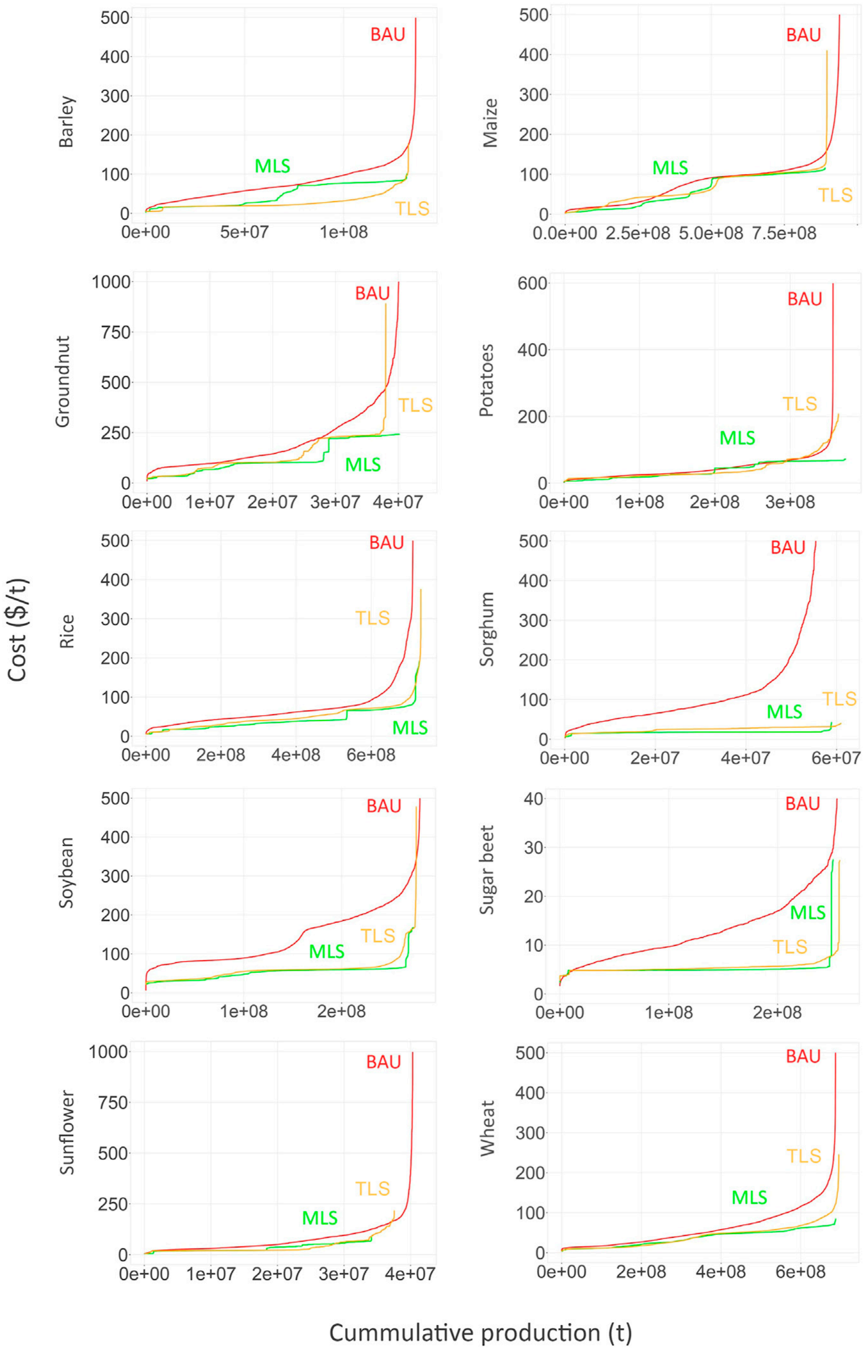

FIGURE 5 | Supply Curves for the 10 crops around the years 2011–2015. The graphs illustrate supply curves representing cumulative production per simulation unit, expressed in tonnes (***t***, horizontal axis) and the corresponding costs (**$/t**, left vertical axis) under BAU and the two land-sparing production scenarios for each of the crops under consideration.

in any given geographical part. With this finding we demonstrate that food demand can be met at a lower cost of production per tonne–a primordial and critical factor to the performance of supply chains (Gold et al., 2017; Validi et al., 2014). We further assess food security implications and investigate costs of energy produced for the 10 crops considered. In this context, food prices were calculated by keeping everything else equal without taking into consideration any dynamic interactions in response to demand or income and employment. Under the present land sparing scenarios, no energy intake loss is due to occur as costs per Mcal produced decrease (**Figure 6**). This is of essence to the current consensus where studies attempt to enhance global food security through the utilisation of crop-based solutions (Aiking, 2011; Day, 2013; Young and Skrivergaard, 2020). Naturally, as the optimisation spatially reallocated agricultural systems globally,

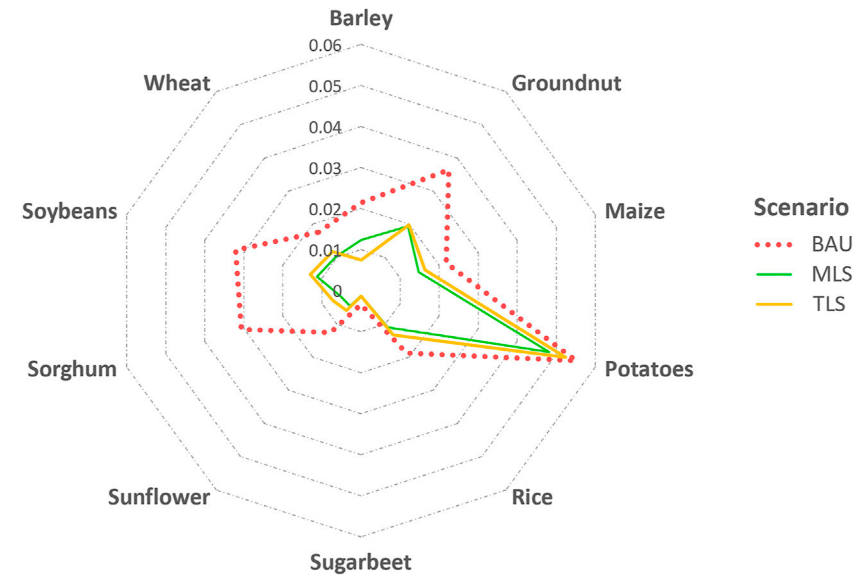

FIGURE 6 | Costs of energy production for the 10 crops considered (USD per Mcal of energy produced).

parts of the globe would rely on trade to achieve production inputs sufficiency (fertiliser) along with feed sufficiency – factors that affect food security in far deeper ways than merely yield gaps (Savary et al., 2012), which calls for robust global supply chains to assure resilience and constant food supply (Seekell et al., 2017; Cole et al., 2018; Kinnunen et al., 2020). Interestingly, MLS and TLS supply curves often intersect, indicating which of the two strategies would result in the most economically efficient system at any given simulation unit. The latter signifies the potential value of a crop-specific, spatially targeted integration of land sparing strategy to best facilitate increased food production at the minimal economic and environmental cost.

DISCUSSION AND CONCLUSION

The effects of environmental conservation on agricultural commodity prices have been highly disputed in the academic literature where it has been indicated that trade-off relationships exist between food security and strategies for conservation (Tscharntke et al., 2012; Pannell et al., 2014; Frank et al., 2017). Here, we develop a cost engineering framework that combines biophysical and financial information of agricultural production systems for ten major crops and compare cost-effectiveness gains between current production practices (BAU) and two land-sparing alternative scenarios (MLS and TLS). Our analysis shows that through a global lens, land-sparing production practices would enable yield-gap closure and thus, allow almost 50% of current cropland extent to be spared which results in lower agricultural production costs than the existing production practices. Findings in the present study demonstrate that the examined land sparing production scenarios reduce aggregate food costs by up to 40% at a global scale.

Closing yield gaps is subject to technical and knowledge requirements with emerging externalities mostly across social dimensions. Concerning the former, our study provides a closed system cost assessment of best available technologies (BAT) (OECD, 2018) where new food production technologies (Herrero et al., 2020) are not accounted for, while the additional yield improvements are not due to better genetic material or plant protection. Specifically, increased yields per unit of land result from intensified application of sufficient nutrients to meet plant requirements and the optimal spatial reallocation of production systems that takes advantage of biophysical characteristics. Moreover, lack of essential knowledge poses a significant barrier in implementing efficient production practices to close yield gaps (Lobell et al., 2009) while lack of credit to respond in production inputs requirements limit agricultural production (Tittonell and Giller, 2013). Seasonal forecasts are not yet good enough to supply farmers with the confidence they need in a highly variable (and therefore risky) environment. As Hochman et al. (2013) demonstrate, risk-averse farmers are hesitant to supply crops with enough N fertiliser unless they are convinced they will earn a good return on investment at harvest, which results in many farmers underapplying N. Therefore, across developed countries with expert farmers, the problem is related to lack of knowledge for best crop rotation (Hochman et al., 2020), based on their location, rather than lack of essential knowledge as well as uncertainty due to high seasonal climate variability. Performance based payments could be motivated as a suitable policy (instrument) option incentivising yield gap closure or it could even be part of sustainability contracts in business practice. The respective environmental accounting standards will need to be developed as the benefits of yield gap closure are accrued through indirect land use effects of local intensification. Regarding social externalities, studies have already addressed the diverse social implications from such strategies (Schleicher et al., 2019) that may affect local food self-sufficiency (Folberth et al., 2020) but also trigger contractions in agricultural incomes, and adversely affect economically local rural populations, imposed by inherently unequally distributed agro-economic efficiencies (Grau et al., 2013). In this context, a range of policy measures have been proposed to financially compensate for abandoned cropland, best manage re-established vegetation as well as exchange knowledge and co-operate infrastructure in order to incentivise implementation of cropland sparing (Phalan et al., 2016).

We contest the longstanding hypothesised trade-off relationships between food security and strategies for conservation and point out that release of cropland does not necessarily entail expansion of costs for the production of agricultural commodities and thus, does not lead in increased food prices. Even though the latter is a result of many factors, long-run food prices are bound to continue to decrease along with historical trends if systems produce more efficiently and close yield gaps by switching where (agro-climatically favourable locations) and how (high-yield farming) food is produced. There is no reason for food prices to escalate in the long-run, neither under business as usual production strategies nor with the implementation of strong policies promoting land sparing.

Policies promoting land sparing could be productivity-based policies that switch subsidies from decoupled payments to a subsidy system that rewards higher yields and environmental goods thus, promoting economic growth from practices enhancing sustainability rather than diminishing natural capital (Tanentzap et al., 2015). In that context, owners of fertile land are encouraged to take up effective reward-by-result options that further promote improvements of farming efficiencies in food production systems (Merckx and Pereira, 2015). Through this location-specific focus, outcome-based payments are being spatially targeted and this improves their economic efficiency, as different locations will have different cost-effectiveness in delivering any given environmental benefit (Reed et al., 2014). Result-based payments provide opportunities for achieving biodiversity objectives effectively, allowing flexibility for the farmers in the management practices chosen to achieve the environmental goals thus, encouraging farm innovation and cost-efficiency (Matzdorf and Lorenz, 2010; Magda et al., 2015; Russi et al., 2016). To achieve environmental outcomes, high-yield farming associated with land sparing strategies needs to be combined with allocation of land for conservation elsewhere (Phalan et al., 2016; Finch et al., 2019). Therefore, the marginal (less productive) land is going to be spared for ecological restoration therein, production systems existing on such landscapes, would be encouraged financially to take up ecosystem services options such as compensation for land left out of production and for planting woodland clusters (Rey Benayas and Bullock, 2012; Zahawi et al., 2013). Land governance, is a rather complicated process where multiple dynamics compete with each other to produce food, conserve natural values or achieve both at an optimally minimal trade-off between the two (Hodgson et al., 2010; Garnett and Godfray, 2012). Thus, to bridge the global targets it is imperative that strategies will lead to effective environmental conservation without delivering unequal socio-economic burdens (Ellis, 2019) and this probably emerges as one of the most significant challenges for the land sparing strategies implementation (Phalan et al., 2016; Folberth et al., 2020).

This analysis provides an evidence-based comparison of how land-sparing production strategies affect agricultural production costs at a global level. However, our framework does not account for the other dimensions of systems transition relative to local constraints, and specifically technical, knowledge, and financial capital limitations. While it is unrealistic to assume that systems change would be independent of these parameters, it can be rationally hypothesized that best available technologies and management practices applied locally will enhance this process. In addition, our model ignores the effects of global cropland reallocation on food trade and while large shares of the worldwide population depend on food imports (26–64%) (Kinnunen et al., 2020), we may underestimate the implications for particular regions where the existing trade balances would change under land-sparing alternatives. The analysis of such limitations and effects in a partial equilibrium model will be the subject of future research. Furthermore, our assessment neglects potential impacts of income and prices on food demand patterns. Relevant empirical studies have assessed such implications on food security suggesting that increases in food commodity prices would decrease food consumption or switch demand to less expensive food products but also finding that increase of market prices by 20% would reduce food consumption by 3% by 2050 (Hasegawa et al., 2014, 2018; Baldos and Hertel, 2014; Nelson et al., 2014). Therefore, the relationship between food demand and market prices is found to be less elastic and thus, these effects would have small-scale impacts on our results. Despite these caveats, the land sparing strategies under consideration seem to have the capacity to enhance food availability at a societal level. Further technological and institutional interventions would be of essence to ensure a meaningful transition for the global poor farming systems providing off-farm and diversification options as alternatives to deemphasize or abandon agriculture as the principal livelihood activity (Ritzema et al., 2017; Thornton et al., 2018).

In conclusion, our results suggest that land-sparing production strategies can reduce global food production costs by up to 40%. Achieving such agricultural landscape organisation and the associated cost-effectiveness requires steps to inform policy making and stakeholders about the economic, environmental and food security benefits. Our study could also be extended to explore subnational production systems variability and technological adoption as well as heterogeneity of soil types and properties – factors very critical to the determination of cost functions within agricultural production systems. Yet, the global and empirical approach of our study is imperative for understanding the cost functions and enable the economic evaluation of the optimised spatial rearrangement of food production as a global strategy. Our cost engineering estimations of production of ten basic crops can also enable the discussion of real options for farmers and landholders as well as policy design to enhance food security in a win-win strategy for the economy and the environment.

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. Datasets required for reproducing key results of the crop production cost engineering model are available from https://ora.ox.ac.uk/objects/uuid:933edc45-43f5-43ed-870a-fe0077916923. Data pre-processing, analysis and estimations were carried out in R (R Core Team, 2014) using the package "dplyr" (Wickham et al., 2020), where visualisations and plots were created using the packages "ggplot2" (Wickham, 2016) and "raster" (Hijmans et al., 2020). Geographical visualizations of results and inputs were produced with ESRI ArcGIS 10.6.1 (ESRI, 2018).

AUTHOR CONTRIBUTIONS

YV and MO contributed to conception and design of the study. YV and CF organized the database. YV performed the analysis and wrote the first draft of the manuscript. SCB, CF, MO, and YV wrote sections 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/fenvs.2021.672663/full#supplementary-material

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Adaptive Governance and Resilience Capacity of Farms: The Fit Between Farmers' Decisions and Agricultural Policies

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Greater resilience is needed for farms to deal with shocks and disturbances originating from economic, environmental, social and institutional challenges, with resilience achieved by adequate adaptive governance. This study focuses on the resilience capacity of farms in the context of multi-level adaptive governance. We define adaptive governance as adjustments in decision-making processes at farm level and policy level, through changes in management practices and policies in response to identified challenges and the delivery of desired functions (e.g. private and public goods) to be attained. The aim of the study is twofold. First, we investigate how adaptive governance processes at farm level and policy level influence the resilience capacity of farms in terms of robustness, adaptability and transformability. Second, we investigate the "fit" between the adaptive governance processes at farm level and policy level to enable resilience. We study primary egg and broiler production in Sweden taking into consideration economic, social and environmental challenges. We use semi-structured interviews with 17 farmers to explain the adaptive processes at farm level and an analysis of policy documents from the Common Agricultural Policy program 2014–2020, to explain the intervention actions taken by the Common Agricultural Policy. Results show that neither the farm level nor policy level adaptive processes on their own have the capacity to fully enable farms to be robust, adaptable and transformable. While farm level adaptive processes are mainly directed toward securing the robustness and adaptability of farms, policy level interventions are targeted at enabling adaptability. The farm- and the policy level adaptive processes do not "fit" for attaining robustness and transformability.

Keywords: CAP, Sweden, resilience capacity, farms, adaptive governance

INTRODUCTION

Farming systems in Europe face increasing uncertainty (e.g. delivering healthy food products, generating adequate incomes, providing good working conditions etc.) due to frequent shocks and disturbances originating from economic, environmental, social and institutional challenges. Resilience is needed for farming systems to deal with these multiple challenges. To be resilient, farming systems should be robust to absorb disturbances, but also to allow adaptations for necessary adjustments and transformations to enable the system to overcome the exposure to disturbances by developing into something new if business as usual is no longer possible (Walker et al., 2004; Darnhofer, 2014; Meuwissen et al., 2019). Recent findings show that the current resilience of European farming systems is mostly oriented toward keeping the status quo (robustness), but farming systems lack the necessary resilience capacities of adaptability and transformability to respond to current and future system challenges (Meuwissen et al., 2020).

There is an increasing recognition that better resilience can be attained through adequate adaptive governance (AG) (Huitema et al., 2009; Djalante et al., 2011; Rijke et al., 2012; Feindt et al., 2020; Mathijs and Wauters, 2020). AG is context dependent and, in practice, applies to problems of a specific system (Walker et al., 2004; Rijke et al., 2012; Chaffin et al., 2014). In this study we define the AG of farming systems as adjustments in the decision-making processes at farm level and policy level, through changes in farm management practices and policies in response to identified challenges (social, environmental, economic) and the delivery of desired functions (e.g. private and public goods) to be attained. AG is necessary when the current state of a system is undesirable, unattainable, or both (Chaffin et al., 2014). That is when the farming system cannot ensure provision of the desired functions such as, for example, securing healthy food products, while attaining high animal and environmental standards, generate adequate incomes, provide good working conditions for employees and ensuring the attractiveness of rural areas (Reisma et al., 2020). The more variability and uncertainty in the provision of system functions, the stronger the need for the decisions to be adaptive (Nyamekye et al., 2018). While delivering the desired functions, AG connects multiple level actors, e.g. primary producers, policy makers, industry and NGOs, in collective action (e.g. Ostrom and Janssen, 2004; Folke et al., 2005; Rijke et al., 2012) to cope with the present (i.e. show robustness), as well as responding to challenges (i.e. enabling adaptive and transformative changes) (Gregg et al., 2015; Mathijs and Wauters, 2020).

Hence, we consider the decisions as adaptive if actors involved in the AG cope with, and respond to challenges. For instance, when coping with a certain challenge e.g. unstable incomes, adaptive decisions will imply short term adjustments that will maintain the income (e.g. via diversifying production). Responsive actions to unstable income might imply mid- and/or long-term technological adaptations and transformations to decrease the dependence of the farm income on the current capacity of the system. In that regard, the resilience capacity depends on multi-level AG, both enabled and constrained by adaptive management processes (herewith AG processes) supporting the system of interest to overcome the challenges (e.g. Gregg et al., 2015). In terms of primary farm production, farmers and policy makers should "ideally" work toward "reaching a desired state" by AG processes at both 1) farm level, e.g. demographics, agricultural practices, financial/risk management (Smit and Skinner, 2002; Meuwissen et al., 2019), and 2) policy level, including interventions with policy programmes, such as the Common Agricultural Policy (Feindt et al., 2019; Mathijs and Wauters, 2020).

Several authors have studied AG of farming systems from the perspective of adaptation decisions and policy interventions (Hurlbert and Pittman, 2014; Morrison and FitzGibbon, 2014; Nyamekye et al., 2018), showing that AG enhances resilience in terms of adaptability. However, from an AG perspective, there remains a lack of clarity and empirical evidence in the scientific literature on how the AG process at farm- and policy level shape and interact to build the resilience capacity, and thus enable farms to be robust, adaptable and transformable. Scholars (e.g. Rijke et al., 2012) are also calling for empirical studies to analyze the "fit" between the AG processes at different levels (e.g. farm level, farming system level) and for different purposes, because AG emerges from the interaction between multiple stakeholders, with multiple functions. Hence, which processes are involved and how they "fit" will depend on the stakeholders considered. Furthermore, in line with the general tendency in the literature on socio-ecological systems (SES), the empirical applications are mainly for environmental and/or climate challenges (e.g. Anderies et al., 2013; Chaffin et al., 2014). However, according to Folke et al. (2005), giving priority to a specific group of challenges may lead to too narrow decisions, which will not guide the system toward sustainable outcomes.

In this study we focus on the resilience capacity of farms in the context of multi-level AG. This approach follows the literature (e.g. Anderies et al., 2013; Meuwissen et al., 2019), where AG is expected to contribute to enhance the resilience capability of a system along the three resilience capacity dimensions. The aim of this paper is two-fold. First, to analyze how AG processes at farm- and policy level influence the resilience capacity of farms in terms of robustness, adaptability and transformability. Second, we investigate the "fit" between the AG processes at farm- and the policy level, to enable resilience. We study the primary egg and broiler production in Sweden, taking into consideration economic, social and environmental challenges. We use semi-structured farmer interviews to explain the AG processes at farm level, and analyze policy documents from the Common Agricultural Policy (CAP) program 2014–2020, to explain the intervention actions taken by the CAP.

CONCEPTUAL FRAMEWORK: FARM LEVEL AND POLICY LEVEL ADAPTIVE PROCESSES SHAPING THE RESILIENCE OF THE FARMS

Much of the AG literature explains the governance of SES in terms of resilience. Building on recent work by Meuwissen et al. (2019), we define resilience of the farming systems as its ability to ensure the provision of the system functions in the face of economic, social, environmental and institutional shocks and stresses, through capacities of robustness, adaptability, and transformability. Robustness is the capacity of the system to absorb disturbances; adaptability is the ability to proceed with necessary adjustments; and transformability refers to being able to overcome the exposure to disturbances by developing into something new (Walker et al., 2004; Darnhofer, 2014; Meuwissen et al., 2019). To be resilient, farms should be resistant to changes, i.e. robust, adaptable and allow transformations (e.g. Meuwissen et al., 2019).

Higher resilience can be achieved by adequate multi-level AG processes (Huitema et al., 2009; Djalante et al., 2011; Rijke et al., 2012; Feindt et al., 2020; Mathijs and Wauters, 2020), involving processes by a range of actors. In terms of AG of farming systems, specifically for the primary production both farmers and policy makers (Darnhofer, 2014; Nyamekye et al., 2018; Meuwissen et al., 2019) influence adaptive processes, and thus shape resilience. The system's resilience capacity is an outcome of these processes, which cannot be reduced to either side (Resilience Alliance, 2010). Hence, in this study we understand AG as adjustments in decision making in both farm- and policy level through changes in farm management practices and policies in response to identified challenges (social, environmental, economic and institutional) and the desired state to be achieved.

Analytical frameworks applying resilience thinking (Meuwissen et al., 2019) and AG (Nyamekye et al., 2018; Smit and Skinner, 2002) of farming systems distinguish between farm level and policy level decisions, where a variety of AG processes and mechanisms are crucial features for the resilience of the farms. For instance, farms bring labor, capital and knowledge to the production process (Darnhofer et al., 2010b; Noe and Alrøe, 2012), and shape the resilience of the farm through multiple AG processes on demographics, agricultural practices, financial/risk management (Meuwissen et al., 2019; Smit and Skinner, 2002). Demographics includes: 1) the dynamics of labor in the farming system, such as: hired labor force, generation renewal by succession; 2) the structure of the agricultural labor force, such as age, qualification, gender, origin; 3) socio-economic issues related to income level, long working hours, remote locations (Bijttebier et al., 2018). Agricultural practices refer to, for example, technological solutions (e.g. organic farming technology, robots), farming routines, and so forth. Risk management relates to strategies for dealing with risk, such as diversification activities, sharing resources, building human capital, openness to learn, applying new ideas and novel approaches, cooperation, etc. (Meuwissen et al., 2019; Spiegel et al., 2020). Themes of farm level adaptive process are summarized in Table A1, **Supplementary Appendix S1**. Current research indicates that at the farm level, robustness is mainly ensured through temporary reallocation of resources, primarily labor and capital, such as finances, equipment and machinery (e.g. Darnhofer et al., 2010b; Darnhofer, 2014). Adaptability implies adjustments to changing context or preferences of employees (predominantly family members), the use of new technologies or access to new markets, responses to climate change and environmental requirements, the acquisition of new knowledge and skills, and so forth. Transformation is triggered by crizes (excessive work load, debts, etc.), and takes place when farmers see their farms as dysfunctional units not able to deliver the desired output (Darnhofer, 2014).

Farm resilience can be facilitated or hindered by the CAP (Feindt et al., 2020; Mathijs and Wauters, 2020). CAP should assist farms to maintain the status quo (if/when the status quo is desirable), but also to help them adapt and transform when needed (Buitenhuis et al., 2020; Mathijs and Wauters, 2020). Given the CAP framework, the expectation is that policy measures will support farmers' income and viability, enable generational renewal, foster innovations, strengthen European rural areas and therefore increase the resilience of the farming systems (European Commission, 2017, 2020). Except for recent studies by Feindt et al. (2019), and Mathijs and Wauters (2020) based on the analytical approach by Buitenhuis et al. (2020), the academic literature on resilience does not provide a systematic assessment capturing the effect of the CAP on resilience (robustness, adaptability and transformability). Hence, in this study we build upon the work by Buitenhuis et al. (2020).

Buitenhuis et al. (2020) introduced the Resilience Assessment Tool (ResAT) to provide a systematic set of key indicators and their respective characteristics for resilience-enabling policies. ResAT aims to explain to what extent current policies at the member state level, and in particular the CAP, enable or constrain the resilience of farming systems along the dimensions of robustness, adaptability and transformability. The key indicators, and anchor examples/characteristics for policy measures enhancing the resilience capacity in terms of robustness, adaptability and transformability are provided in Table A2, in **Supplementary Appendix S1**. Within the ResAT approach, based on an extensive literature review, the authors identify four key indicators for each type of resilience. Key indicators of robustness enabling policies are: 1) short-term focus for recovery and continuation of the status quo with marginal adjustments; 2) protecting the status quo by marginal adjustments; 3) buffer resources to enable the availability and accessibility of; and 4) preventing risk measures. Key indicators of adaptability enabling policies are: 1) middle-to long-term adaptations; 2) flexiblity, to allow actors to respond; 3) variety of system solutions (diversification, ecosystem services); and 4) social learning. Finally, key indicators of transformability enhancing policies are: 1) long-term focus, i.e. policies address a time span of over five years to decades; 2) dismantling incentives to prevent status quo/to support transformative practices, 3) in-depth learning; and 4) enriching and accelerating niche innovations and experimentation, see Table A2, in **Supplementary Appendix S1**. The resilience AG process at farm level and policy level influencing resilience capacity in terms of robustness, adaptability, and transformability are summarized in **Figure 1**.

AG processes at farm- and policy level should interact in order to "reach a desired state". The "desired state" should be identified by the actors involved in the system of interest (e.g. farming system), and may refer to the delivery of a variety of functions representing private and/or public goods

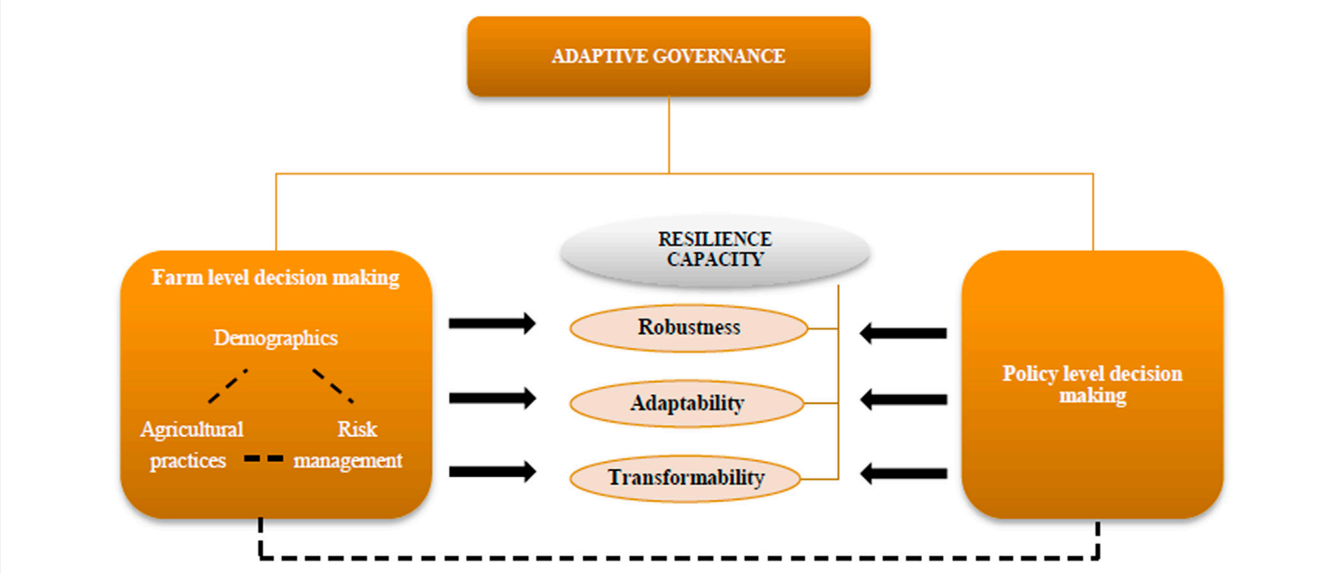

FIGURE 1 | Adaptive governance processes: farm level and policy level adaptive processes influencing the resilience capacity of farms.

(Meuwissen et al., 2020). In the literature, this is known as "fit/misfit" (e.g. Huitema et al., 2009; Chaffin et al., 2014) or "connects/disconnects" (Termeer et al., 2019) between the AG processes and the system of interest. Rijke et al. (2012) introduce the concept of "fit-for-purpose" governance to be used as an indication of the effectiveness of governance structures and processes to fulfill a certain objective at a certain point in time. It is expected that the AG processes provide a framework for solutions for the farm challenges, enabling farms to deliver the main functions, hence the resilience. The question about the "fit" can be posed for different purposes (Rijke et al., 2012). In our study we use the "fit" approach to evaluate the potential effectiveness of policy to support farm level AG processes to deal with the challenges and deliver the desired functions and thus stimulate the resilience of farms.

"Misfits" can arise as a result of gaps in the AG processes at farm level and/or policy level, disenabling the farms to manage their resources or activities or deliver the essential functions (Ekstrom and Young, 2009). Identifying "misfit" is a critical step of identification of underlying gaps in AG processes (Ekstrom and Young, 2009; Rijke et al., 2012). In our study, the results on the "fit" will bring attention to insights for potentially inappropriate AG processes for robustness, adaptability and transformability.

To sum up, this paper studies the multi-level character of AG to shape the resilience of farms. The study differentiates between farm level ("demographics", "agricultural practices" and "risk management") and policy level AG processes. We incorporate the resilience concept as put forward by Meuwissen et al. (2019), considering: 1) existence of three resilience capacities: robustness, adaptability, and transformability, and 2) multiple challenges: economic, social, environmental and institutional.

METHODOLOGY

Case Study: Functions and Challenges

AG is context dependent, where different practices of farm level and policy level decision making are case study specific (Rijke et al., 2012; Chaffin et al., 2014). To assess how AG shapes the resilience of a system, one must specify which functions are of interest and to which challenges they might be vulnerable (Carpenter et al., 2001; Meuwissen et al., 2019), so that action can be taken (Cabell and Oelofse, 2012).

The Swedish commercial egg and broiler production are among the most prosperous agricultural productions in Sweden, where family farms constitute about 95% of all farms (Jordbruksverket, 2015). Both egg and broiler production is growing fast, and since 2010 has increased in volume by 34% in the egg sector and by 36% for the broiler sector (Jordbruksverket, 2020a; Jordbruksverket, 2020b). Both egg and broiler producers are strongly oriented toward production for domestic markets, where production of safe food, viable incomes, low nutrient loss, animal health and welfare, and farm employment are among the desired functions. However, despite the prospering market, egg and broiler production are under constant pressure from institutional, societal and environmental requirements for ecologically and animal-friendly production, and farms face steadily increasing production costs. Challenges and the desired functions identified for Swedish egg and broiler production are summarized in **Figure 2**.

Since 2000, the Swedish egg and broiler sector has been constrained by various challenges, in particular meeting new requirements for food safety, animal health and animal welfare (Regeringskansliet, 2015). These issues are debated by a wide range of actors at different levels, e.g. producers, processors,

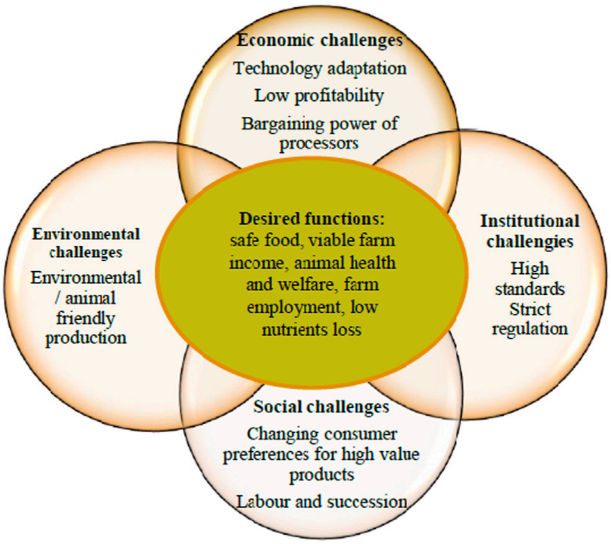

FIGURE 2 | Toward desired functions: main challenges identified for Swedish egg and broiler primary production.

consumers, NGOs and governmental bodies. In Sweden, animal welfare is considered a public good (Petitt and Bull, 2018). According to governmental documents (Regeringskansliet, 2015), Swedish standards for animal welfare and disease protection are higher than most of the EU directives and regulations. The main challenges imply that this makes production costs higher, and thereby the Swedish broiler and egg producers are uncompetitive on price (Jordbruksverket, 2018b). The increased costs are expected to be offset, due to consumers' higher willingness to pay for the relatively higher levels of animal health and welfare standards.

Following market liberalization after joining the EU and its internal market in 1995, the relatively high costs (compared to other EU member states) for inputs such as labor, energy and especially feed prices put pressure on Swedish farmers to continue with structural investments in order to remain competitive through increased productivity (Regeringskansliet, 2015). Dependence on processors (slaughter houses and egg packaging companies) leads to low value added at farm level and thus low margins for the two types of production (Bijttebier et al., 2018). Generational change, gender balance and lack of skilled workers are among the commonly identified social challenges.

Data Collection and Analysis

A qualitative approach was adopted to analyze both farm- and policy level AG. This approach was appropriate as the aim was to generate deep insights and context-dependent narratives at the farm level, as well as a deep understanding of the extent to which policy constrains or enables resilience. Firstly, 17 semi-structured interviews were conducted with farmers/farm employees during 2018 in order to understand the farm management practices that they employ in order to remain resilient (Coopmans et al., 2019). Secondly, a content analysis of policy documents on CAP for the period 2014–2020 was conducted to determine to what extent policies enable or constrain the resilience capacities of robustness, adaptability and transformability. By analyzing both farm- and policy level dimensions, we are seeking to better understand the interplay and "fit" toward assuring robustness, adaptability and transformability of the farms.

Semi-Structured Interviews with Farmers and On-Farm Employees

Semi-structured interviews (Wengraf, 2001; Silverman, 2017) were conducted during the summer of 2018 and included respondents from six farms (4 conventional and two organic) in the southern part of Sweden, where most of the egg and broiler farms are located. We employed purposive, non-random sampling, not aiming to reach statistical representativeness, but to cover as much diversity as possible with as few respondents as possible. Within each farm, several interviews were conducted, involving different respondents with different roles and experience (e.g. young active farmer, old active farmer, the spouse, successor/future successor and employee). The rationale behind involving respondents with different roles was to gather all opinions of importance for the farm. Respondents were not randomly chosen, but specifically selected according to the occupational status and the characteristics of the farm (Coopmans et al., 2019; Denzin and Lincoln, 2000). The main characteristics of the farms and the respondents participating in the semi-structured interviews are resented in **Table 1**.

Farms and their associated respondents were not randomly chosen, but specifically selected in order to reach a diverse sample in terms of respondent type and farm situations. As a case study, the results are not intended to be representative of the egg and broiler farming system as a whole, but provide a good illustration of the likely resilience capacities across the sector (Denzin and Lincoln, 2000).

An interview guide was used to ensure consistency in the questions asked across the interviews. Reflecting the conceptual framework that defines farm level adaptive processes along the dimensions of farm demographics, agricultural practices and risk management, respondents were invited to talk about the historical trajectory of the farm, particularly in terms of what challenges had been faced over time, and what coping strategies the farmer had employed in order to deal with them. Questions also focused on how various factors, such as farm demographic change, family relations, objectives for the farm, uptake of new technologies were perceived as influencing the farm's resilience. Themes and guiding questions used for the farm interview are provided in Table A3, in **Supplementary Appendix S1**. All interviews were conducted by two researchers, and lasted between one and 1.5 h. Interviews were audio recorded (with the consent of participants) and transcribed verbatim.

Qualitative thematic analysis was undertaken on the transcripts (Creswell, 2013), using NVivo 12 Pro software (QSR, 2018). Coding involved aggregating the text into categories or themes by coding text fragments to various thematic codes (Auerbach and Silverstein, 2003). A short set of provisional codes was first identified from the research questions in the study, but these were expanded inductively as

TABLE 1 | Characteristics of farms and respondents participating in the semi-structured interviews.

Farm and respondents characteristics		Farm 1	Farm 2	Farm 3	Farm 4	Farm 5	Farm 6	No
Production specialization	Broilers	1			1	1		3
	Eggs		1	1			1	3
Production orientation	Conventional	1	1	1	1			4
	Organic					1	1	2
Respondent	Farm owner/manager	1	1	2	1	1	1	7
	Successor		1		2	1	1	5
	Other person taking over the farm	1						1
	Employee		1	1			2	4
Gender	Male	2	2	2	1	2	3	12
	Female		1	1	1		1	5

Note: In the table, the numbers represent the total number of farms and respondents in the respective production specialisation/orientation, and in the respondent/gender category.

coding proceeded, with additional codes added, or existing codes revised (Creswell, 2013). The codes included the three resilience capacity dimensions (robustness, adaptability and transformability) and strategies adopted by respondents across the farm level adaptive processes of demographics, agricultural practices and risk management (see Table A1 in **Supplementary Appendix S1** for the final set of codes). Although participants did not necessarily use the specific terms robustness, adaptability or transformability, attributes that reflect these capacities were identified and thus coded into the relevant thematic code.

In order to minimize researcher bias, three researchers were involved in coding and interpretation of the data. Each transcript was coded and interpreted independently by two researchers, who then compared their coding to check for consistency or differences in coding. Differences in interpretations were registered and further discussion was undertaken by the three researchers in order to determine the final analysis.

Policy Document Analysis

Firstly, relevant policy documents were identified by the researchers. These included 1) national CAP documents, such as basic payment schemes and the rural development program (RDP), over the 2014–2020 period, and implementation plans for 2017 and 2018; 2) EU documents on the CAP for the policy program 2014–2020. In total, eleven documents were identified, providing an overview of the existing policy instruments (see **Supplementary Appendix S2** for a list of the selected policy documents).

A content analysis was undertaken on the documents to investigate the extent to which the current CAP in Sweden enables or constrains the resilience of the egg and broiler sector in terms of robustness, adaptability and transformability (e.g. Buitenhuis et al., 2020). Firstly, the identified documents were imported into Nvivo 12 Pro software (QSR, 2018) and analysis proceeded by coding sections of the documents to a coding framework developed from Termeer et al.'s (2018) ResAT tool. Thus, codes included type of resilience, key indicators of resilience and examples of how the indicators are enabled by policy instruments (Termeer et al., 2018) (see **Supplementary Appendix S2**). Validation of the results from the policy document analysis was undertaken by face-to-face interviews with two stakeholders (one policy analysist and one specialist in poultry production) and a focus group with eleven stakeholders, all working with agricultural policy evaluations.

Finally, the results from the farm level and policy level analysis were compared to identify the "interplay" and "fit" between these two operational levels of AG in response to the identified challenges and desired functions.

RESULTS AND DISCUSSION

This section presents and discusses the main findings on: 1) the key farm level and policy level AG processes that shape the robustness, adaptability and transformability of the farms, and 2) the "fit" between these two operational levels of AG in response to the identified challenges and desired functions.

Adaptive Processes Enabling Robustness

Farm Level Processes Enabling Robustness

At farm level, "farm demographics" and "risk management" are the main categories of AG processes shaping the robustness of the farms in the case study. These processes are generally responsible for securing resources, such as labor, financial capital and social networks.

Through our interviews, farming was seen "as a lifestyle" involving long and irregular working hours, seasonal shifts, and informal and unpaid labor. One of the *respondents described the farmers' lifestyle as a 24-h job:* "You are on-call 24 h per day"*. Under such circumstances,* the family, especially the wife's involvement was explained as crucial for the robustness of the farm. Women were also often declared responsible for '*soft values*', close to the chickens, as several informants believed that women have an '*eye for animals*' that men do not. Administration was also among the tasks mostly carried out by women, especially with the increase in bureaucratic work load. Generational shift was seen as a "natural process" but required early involvement of offspring in "farm life". To decrease the risk of high reliance on family members and individuals who know the particular farm operation, farmers try to improve human capital, as illustrated by this respondent: "*not rely on only one person - farming activities need to be maintained when anyone in the family get sick*". They do this by providing training for family members or hired staff, and thus securing farm labor to be able to perform tasks independently or to take over for a period of time when the responsible farmer is absent. Family members taking off-farm jobs were seen by the respondents as a "risk management" strategy to buffer farm economics, but also to adapt farm labor in periods when the need for labor changes. The 'risk management' strategy to build good relations and cooperation with neighbors was important. It increases interactions and social wellbeing, but also the willingness to support each other with labor and machinery, or to share opinions and provide help with unforeseen events on the farm, and thus contribute to its robustness.

Results from our study show that farm level decisions have a great influence over the use of resources (as in: Resilience Alliance, 2010), and adaptations on farm labor involvement building human capital and networks are among the most common (e.g.,Smit and Skinner, 2002; Darnhofer, 2010). Smit and Skinner (2002) showed that diversifying income through off-farm employment provides robustness for farms facing crizes. Moreover, the authors showed that combining different types of information and sharing this in various networks is important for identifying partners for joint ventures when attractive opportunities arise. Cooperation has also been explained as important to avoid the isolation of working on one's farm and to maintain social life in the rural community (Smit and Skinner, 2002; Ashkenazy et al., 2018). 'Risk management' strategies secure social capital through knowledge building and financial capital through diversified on-farm and off-farm incomes (Darnhofer, 2010; Bertolozzi-Caredio et al., 2021), but also facilitate positive farm demographic trends for increased interest of the younger family members to continue the farm business (Darnhofer, 2010). From a social point of view, possibilities for diversification allow each family member to find activities that correspond to their personal preferences and interests, in that sense improving the job satisfaction as a key component to quality of life, and thus to ensure farm succession. However, Darnhofer (2010) does not relate farm strategies with resilience capacity dimensions.

Policy Level Processes Enabling Robustness

The CAP in Sweden is not oriented toward securing the robustness of farms' "short-term objectives", but rather toward "mid- and long-term" objectives (Regeringskansliet, 2014) which are targeted toward enabling adaptability and transformability (Termeer et al., 2018; Buitenhuis et al., 2020): "In Sweden, the agricultural policy is intended to be designed in as long term as possible (Regeringskansliet, 2014, *p*. 9), with liberalized, market-oriented and competitive agricultural sector driven by the consumers demand and taking into account climate, environment, animal welfare and development (Regeringskansliet, 2014, *p*.112)".

Within the CAP, robustness is partially maintained via direct farm payments which 'protect the status quo', however these payments are not coupled to egg and broiler production:"Direct payment is provided per ha land and is aimed at "supporting farm income" as it adds to farm income in a direct way (Regeringskansliet, 2014, *p*. 111; European Commission, 2016, *p*. 23). Hence, the influence of this measure is indirect through on-farm fodder production, as it is provided per hectare utilized. Income stability risk measures are not provided. The policy expectation is that 'soft' robustness-oriented policies will increase the risk aversion of farmers and initiate adoption of "risk preventive measures", enabling the farms to secure their incomes by investments and knowledge (e.g. to prevent spreading of pathogens and diseases, work related injuries, etc.). Risk "preventive" measures such as support for modernization of stables, improved work environment, knowledge acquisition, etc., are incorporated in the rural development program. In terms of securing on-farm labor, young farmer payments are provided to facilitate generational shift, but the instrument is more oriented toward mid-term planning, thereby adaptability. Short-term labor variations (day-to-day, seasonal, etc.), are not considered.

Research findings have shown that policy measures for income stabilization have a potential to alter the funds available to farmers to reduce the risk of income loss as a result of increased incidence, severity and duration of disaster-related events (Smit and Skinner, 2002; Feindt et al., 2019; Meuwissen et al., 2019; Bertolozzi-Caredio et al., 2021). However, such measures can discourage changes in land use and production practices. For instance, insurance measures have been associated with lower levels of off-farm income, less diversification, e.g. products and inputs, spatial diversification, resistant crops, etc. (Smit and Skinner, 2002).

Adaptive Processes Enabling Adaptability

Farm Level Processes Enabling Adaptability

"Risk management", including diversification, building human capital and networks, changes in "agricultural practices", e.g. applying new technologies, are the main farm level processes enabling the adaptability of the Swedish egg and broiler production, identified in our study. On-farm diversification, e.g. forest, horses, pigs, fodder production, tourism, was represented as a "risk management" strategy used to secure the farm from being dependent on sole income.

From the "risk management" strategies, building good relationships with farmers and surrounding networks (advisory services, industry, authorities) for sharing knowledge, was seen as important for the adaptability to changing circumstances in terms of farm enterprise development and demographic change, as demonstrated by one farmer: "And later in the evening, when my brother was at the local store doing some shopping, he ran in to an old friend who said: "Do you know anyone who is hiring? I have a boy at home dwelling around". 'Well, send him over', he had answered. And now he is here."

Participants considered "risk management" decisions to change the "agricultural practices" by adopting advanced technical solutions central to the development of the farms, as it allows for adaptation in terms of labor (as less manual labor and fewer working hours are needed), but also for dealing with challenges related to meeting regulatory environmental/animal welfare, and consumer requirements: *"Rregulations are complex and require a lot of work, but one simply has to adjust to adjust the production to them"* and "*I don't want to see regulatory changes in Sweden, I want to see them in the EU*".

New machines and robots, particularly within egg production have helped to eliminate heavy physical work, which previously limited the opportunities for older farmers and farm workers to continue working: "We stacked six trays on top of each other. They each weighed 12 kilos." [...] "Well, for someone who's young it's no issue, but we have people over 60 working here, and that wouldn't have worked very well."

Applying organic farming technologies is in accordance with new market trends and consumer and societal preferences for safe/organic food: *"Well it is possible to adjust, so that you can follow the market"* [...] *"In the meanwhile we have become more and more ecological because chicken manure is eco-approved"* [...] *"There is a financial incentive when we see that we can make more money if we invest."*

Findings are in line with the resilience literature, where diversification is a well-established "risk management" strategy for enhancing adaptive capacity in general (e.g. Darnhofer et al., 2010a; Darnhofer, 2014; Ashkenazy et al., 2018). Diversification helps in the reorganization of resources, which as a consequence increases farmers' room to maneuver (Darnhofer et al., 2010a), and secures different sources of income for the farm household (Knickel et al., 2018). From a case study analysis including 14 EU countries, Ashkenazy et al. (2018) identified three main clusters of diversification toward adaptability: finding new products, creating new ways to structure supply chains and initiating new activities; all requiring farmers to devote resources and to develop new skills, and to undertake new operations. Through a literature review analyzing farm adaptive management approaches, Darnhofer et al. (2010a) and Darnhofer (2010) showed that in addition to diversity, learning, sharing information, building networks and flexibility are key strategies of farm level actions recognized as appropriate for adaptability. Learning, experimentation, and flexibility have also been emphasized as ways to achieve adaptability for institutional (formal governance) adaptive processes of SES (Huitema et al., 2009).

Policy Level Processes Enabling Adaptability

At the level of the policy process, adaptability is expected to be achieved mostly via support that facilitates a "mid-term solution for adaptations", "variety of system solutions", and social learning, mainly focusing on environmental and climate objectives. The support for environmental and the climate objectives takes a large share of the Swedish CAP, with 63% of the total budget allocated to restoring, preserving and enhancing ecosystems related to agriculture and forestry (European Commission, 2016, *p.* 324).

In regard to "mid-term solutions for adaptations", "variety of system solutions" support is provided to enable restructuring and modernizations of buildings providing good animal welfare, replacement and use of energy effective technology and innovative methods (Regeringskansliet, 2015, *p.* 208–209), thus helping farms to adapt to environmental and climate requirements (Regeringskansliet, 2015, *p.* 225). Support for cooperation and pilot projects is expected to help for enhancing skills, the ability to manage and lead companies and spreading good examples of business models (Jordbruksverket, 2017, *p.* 51–52). Furthermore, the support for ecological production is expected to have positive effects on the environment, climate, animal health and rural development (Regeringskansliet, 2015, *p.* 450), foster creation markets and products with high value added. In budgetary terms (total public funding), support for organic farming (nearly 12% of the total budget) is among the four biggest RDP measures contributing to both the economic and environmental targets (European Commission, 2015). Within CAP, special emphasis (both within Pillar one and Pillar 2) is given to the need for young farmers to enter the farm, and thus ensure the domestic food production and, consequently, the production of collective goods (Regeringskansliet, 2014, *p.*112,; Regeringskansliet, 2015, *p.* 79 and 91,; Jordbruksverket, 2018a, *p.* 7). Last but not least, *knowledge/competence development, knowledge transfer measures* are in place to facilitate the environmental/climate adaption. Such measures are expected to help farmers to receive practical/individually adjusted advice and in that way to develop, to be market oriented and to adjust to the environmental requirements and climate change. (Jordbruksverket, 2017, *p.* 18 and 26,; Jordbruksverket, 2018a, *p.* 17, *p.* 17)**.**

"Social learning" is enabled by policies designed to promote social activities/inclusion and local development in rural areas, and can be expected to be fostered by instruments for building infrastructure necessary for social learning development such as: a quality broadband network in rural areas (Regeringskansliet, 2015, *p* 270), developing products, methods, processes and techniques to share knowledge (Jordbruksverket, 2017, *p.* 64), investment for rural services and leisure to keep the local service in the rural areas, and provide possibilities for sport, leisure and meeting rooms (Regeringskansliet, 2015, *p.* 287). In Sweden 22% of the total RDP budget is allocated to the development of rural areas (European Commission, 2016, *p.* 324). Knickel et al. (2018) have identified knowledge and learning among the most important instruments for initiating changes, playing an important role in EU rural development policy.

Adaptive Processes Enabling Transformability

Farm Level Processes Enabling Transformability

At farm level, shifts in "agricultural practices" was identified as a main AG process shaping transformability. From the interviews it was clear that triggers leading to transformability were "*unforeseen coincidences*" or the farmer seeking a chance to increase profit. This could have been an opportunity to buy a farm that was suited for a certain kind of production, or the main processing company asking the farmer to join the production. *Interviews provided* several examples where farmers' decisions to transform their businesses were a response to a request or push from the industry. For instance one farmer indicated that he/she was instructed by the industry (a processing company) to convert from turkey to chicken production. Smit and Skinner (2002) also explain the transformations of the "private sector" as "spontaneous", or a combination of "consciously planned and spontaneous" strategies. *In the existing l*iterature, transformation is linked to shifts initiated by both new opportunities and new patterns. A crisis can also be considered a "window of opportunity", enabling transformative change (Darnhofer, 2014). However, the literature has also shown that opportunities that influence the decision-making processes do not always result in decisions taken (Prager and Freese, 2009).

Policy Level Processes Enabling Transformability

At the policy level, transformability is mainly related to "long term" environmental and climate objectives, i.e. the generation of public goods and innovative production. For that purpose, multiple instruments such as support for non-productive investments, support for vocational training and advisory services, organic farming support and support for agri-environment-climate commitments, support for cooperation, building innovation groups and innovation projects with a focus on long-term social, environmental and climate objectives is provided.

Transformability is also supported by "initiatives for niche innovations", enabled by knowledge transfer and information measures (e.g. Regeringskansliet, 2015, *p*. 164), and support for pilot projects and cooperation between the innovation groups (e.g. Jordbruksverket, 2017, *p*. 47). Sweden has allocated 3% of the total RDP budget to knowledge transfer and innovation actions (European Commission, 2016, *p*. 326). However, together with cooperation actions this expenditure increases to 8% and in total 135,000 places on training courses will be provided (European Commission, 2015, *p*. 2). As described in the RDP, vocational training and advisory services are expected to convey new results from research and disseminate innovations (Regeringskansliet, 2015, *p*. 90); support for demonstration is likely to encourage the use of new methods and knowledge (Regeringskansliet, 2015, *p*. 166–167); and courses and information sharing are considered an effective way for spreading innovation (Regeringskansliet, 2015, *p*. 165, 167). Within the EIP special emphasis is put on environmental production where organically produced broilers for fattening are among the prioritized production types, whereas organic egg producers are not (Jordbruksverket, 2017, *p*. 55). In general, the effect of knowledge transfer and information measures on the enhancement and acceleration of niche innovations is indirect, e.g. it increases the awareness/interest to invest/apply innovative production. On the other hand, pilot projects allow different solutions to be tested before they are fully implemented.

According to Knickel et al. (2018), knowledge and learning are key instruments for initiating/inhibiting transformation. Our results show that transformations are highly related with social networks, both at farm level (e.g. industry, other farmers) and policy level (knowledge transfer platforms, cooperation and innovation groups).

What Is the Interplay and the "Fit" Between the Farm Level and Policy Level Adaptive Processes While Building Resilience?

In this study we show that different farm level and policy level AG processes are responsible for shaping the different resilience capacities of the farms. "Demographics" adaptive decisions are mainly related to robustness. "Risk management" strategies enable robustness and adaptability. Changes in "agricultural practices" enable adaptability and transformability of the farm. Policies were found to be mainly oriented toward adaptability, and to some extent for transformability and robustness. A summary of farm level and policy level attributes enhancing the resilience capacities of robustness, adaptability and transformability is provided in **Table 2**.

Smit and Skinner (2002) explain that AG processes are not mutually exclusive and are often interdependent; public policy to "fit" the farm level processes needs to be developed with respect to farmers' adaptive decisions undertaken to deal with the challenges and to deliver the desired functions. Our findings show that among the farm level AG processes, "risk management" and "demographics" interplay for securing robustness. The main common practices are managing labor availability and competence to secure farm activity and thus the social and the economic wellbeing of the farm. Important challenges are the low interest in farming in general, and the involvement of family members and the younger generation. In our study we did not find evidence of policy instruments developed for securing the labor availability/competence for day-to-day/seasonal planning, enabling robustness of the farms. Young farmer payments (to facilitate generation shift) and knowledge-related payments are provided, but the objectives of these instruments are more oriented toward mid-term adjustments, and thus adaptability of the farms. Fischer and Burton (2014) have shown the importance for farm succession of children forming a farming identity at an early age. To "fit" the farm-level adaptive decision making, future policies should also consider: 1) making farming attractive as an occupation, so farmers can have better access to labor; 2) attract farmers to enter farming/become managers at an earlier stage.

Private and public adaptation processes often have interrelated roles in the case of adaptability (Smit and Skinner, 2002). From our results, we see that both farm level adaptive processes, including "risk management" and "agricultural practices", and policy level adaptive processes exist to work mutually for market adaptations, farm modernization and knowledge management enabling adaptability. The AG processes at farm and policy level "fit" to enable compliance with food and environmental standards, changing consumer needs, and securing the viability of farms.

At farm level, transformability is operationalized with "agricultural practices" through spontaneous decisions initiated from the social networks, mainly contact with industry, considered by the farmers as trustful, despite its high bargaining power. The changes applied on the farms were seen as continuous adaptations to requirements for technology change, initiated by regulations and changes in consumer preferences. According to Lebel et al. (2006), proper communication is important for building trust and understanding the need to mobilize resources, in order to foster self-organization. Policy measures for transformation exist in the CAP documents (innovations, experimentation, niche production, etc.) but we did not find evidence for on-

TABLE 2 | Summary of farm level and policy level attributes enhancing the resilience capacity: robustness, adaptability, and transformability.

Farm level processes	Robustness	Adaptability	Transformability
Demographics	• secure labor: generation change, other labor • social networks		
Agricultural practices		• applying new technologies: less labor intensive, agro-environmentally and animal welfare friendly	• applying new technologies, new opportunities or seeking profit
Risk management	• off farm jobs • adapt labor to seasonal needs • good relationship and cooperation	• diversification of farm and off farm income • building human capital • openness to learn, and share knowledge • cooperation: advisory services, industry, authorities	
Policy level processes	• policies to protect the status quo (very limited)	• policies for "mid-term solutions for adaptations to improve the environment, animal welfare, and replacement of old energy inefficient technology • policies for variety of system solutions • policies for social learining	• policies for long term planning and strategies related with agro-environmental and climate strategies • policies for accelerating niche innovations

farm transformations enabled by/related to policies supporting transformation. Knickel et al. (2018) have also found that inadequate linkages between knowledge, innovation and rural development are insufficiently supportive of longer-term adaptive management frameworks. In that regard, for the desired "fit", building proper channels for transferring the knowledge to the farms is needed. That would enable knowledge creation, which can influence transformative decisions on farms (e.g. Nyamekye et al., 2018). In regard to the result obtained for the "misfit" of the policy to enable transformation, it is worth mentioning that in fact, transformative processes take a long time, and the final outcome might be through step-wize adaptation (e.g. Darnhofer, 2014). Smit and Skinner (2002) distinguish between actions for transformations that are undertaken as a regular part of ongoing management activities, from those that are deliberately planned to fulfill specific objectives. In this study, the phenomenon of transformative changes initiated by the CAP that led to adaptations was not observed.

Discussion on the Limitation of the Study

This study focuses on farm level and policy level AG processes, omitting the remaining decision-making levels within the value chain. All actors of the multi-level governance value chain (e.g. industry, consumers, retailers, legislation) contribute to various AG process levels by involving their capacity to enable building resilience of the system (e.g. Ostrom and Janssen, 2004). Our results show clear evidence for the importance of industry involvement in transformative processes on the farm level, such as choosing to be a broiler farmer, or transformation to organic farming. Furthermore, from the results it was clear that adaptations are influenced by consumers' preferences for high value products. However, the interlinkages and the cross-level interactions between the various AG processes at these decision levels were not studied in details. Furthermore, in our study, policy level AG processes are observed only from a top-down approach, showing the potential for the policy to meet the need for the identified challenges. However, this does not automatically imply that the farming system uses the capacity provided by the policy (Buitenhuis et al., 2020). How policies are implemented remains to be investigated.

Analysis using a full set of AG processes at various decision levels can create a system-wide perspective on how the farming system is governed (Ekstrom and Young, 2009). The need for such analysis is confirmed in the research, but as the qualitaive research provides in-depth evaluations which are time intesive, qualitative research examining fit typically focuses on a selected set of AG levels (e.g. Nyamekye et al., 2018).

CONCLUSION

The research presented in this article focuses on the resilience capacity of the Swedish egg and broiler farms in the context of multi-level AG. In particular, the study analyses: 1) which AG processes at farm level and policy level shape the robustness, adaptability and the transformability of the farms and how? and 2) what is the fit between these two levels of AG in response to the identified challenges and desired functions? This is a first attempt to analyze farm resilience in the context of AG while considering the three resilience capacities, i.e. robustness, adaptability and transformability, and multiple challenges identified for the farming system.

Results show that both farm level and policy level AG processes shape the resilience of farms. However, neither farm level nor policy level AG processes on their own have the capacity to entirely enable the farms to be robust, adaptable and transformable. The AG processes have different strengths and weaknesses and are, therefore, to a varying degree, appropriate for the desired functions (as in, for example, Rijke et al., 2012).

The farm level adaptive processes are mainly directed toward securing the robustness and adaptability of the farms. Farmers try to keep and/or adjust production within the existing regime, continuing with eggs and broiler production. In the resilience literature, this is explained as a "conservative notion" used to "stabilize the system and return to normal" (Pike et al., 2010; Darnhofer, 2014). "Demographics" in terms of labor availability and labor division of gender are mainly related to robustness. “Risk management” strategies enable both robustness and adaptability to safeguard financial capital and social capital. Securing social capital, i.e. building knowledge, is crucial for both labor availability for different farm operations, and for adopting new “agricultural practices”. Changes in “agricultural practices” enable the farms’ adaptability for complying with high standards and regulations and changing consumer preferences. Transformability of the farms is also related to changing “agricultural practices”, operationalized by spontaneous decisions when “new opportunities and crizes” appear (as in Smit and Skinner, 2002). The “risk management” and the “demographics” interplay to enable the robustness and the adaptability of the farms. Moreover, “risk management”, “agricultural practices”, and “policy” interplay for adaptability.

The fit between the AG processes at farm level and policy level is evident for reaching adaptability. Common desired functions are delivering safe food, meeting societal and consumer needs for safe food, animal health and welfare, and securing farm employment. In our study, the largest “misfit’ is that between the farm level and the policy level adaptive processes for attaining robustness and transformability. In particular, while robustness at farm level is mainly related with securing labor availability, we did not find evidence of policy instruments developed to help enhance competence for day-to-day and seasonal planning. From a policy perspective, farm robustness is only partially enabled via direct payments as a buffer capacity for capital, but these payments are not coupled to the egg and broiler production. Moreover, while policy attempts are partially present to build infrastructure for future transformations (mostly environmental benefits), applications of transformability-related adaptive practices at farm level were not found. Instead, transformations identified at farm level result from initiatives undertaken by the industry and consumer preferences for high value products. One possible reason for not identifying transformability actions initiated by the policy could be that transformation takes a long time and such responses might be considered as a regular part of ongoing management activities, through step-wize adaptation (e.g. Darnhofer, 2014).

This research contributes to the literature on AG of farming systems. In line with the existing knowledge, findings show that the AG of farming systems is tailored toward adaptability. This raises concerns for future AG operationalisations, where robustness and transformability need to be considered along with adaptability actions. We acknowledge that AG of farms is complex (Smit and Skinner, 2002; Rijke et al., 2012; Ashkenazy et al., 2018) and interpreting and generalization of results on the concept of resilience depends on the system to which it is applied (Knickel et al., 2018). However, our study provides a conceptual framework on AG of farming systems and explains empirically how farm level and policy level AG processes shape the resilience of farms, i.e. the robustness, adaptability and transformability. The study covers economic, environmental, social and institutional challenges, filling the gap in the AG literature, which prioritizes environmental challenges. Results on the fit between the farm level and the policy level AG processes are a valuable input for the policy makers. Recognizing potential misfits between farm level and policy level AG processes may contribute toward building future strategies and actions for improvements in the respective farm resilience capacity, and therefore the resilience of rural areas.

Resilience is a relational issue that can be addressed at different level of governance. Extending the relational perspective from farm level and policy level to the broader farming system environment is crucial for future studies. Future research could consider including other levels of governance, including, for example, industry, retailers, suppliers, consumers, policy makers and a mixed top-down and bottom-up approach (e.g. Rijke et al., 2012; Ashkenazy et al., 2018), with details on how the various multi-level AG processes are planned, operationalized and interplay in the practice.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Legal Affairs Unit of the Swedish University of Agricultural Sciences. The participants provided written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

CRediT author statement: 1. M-TG: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Supervision, Visualization; Writing – original draft; Writing – review and editing. 2. PA: Conceptualization; Data curation; Formal analysis; Investigation; Software; Writing – original draft; Writing – review and editing. 3. LS: Conceptualization; Data curation; Formal analysis; Investigation; Software; Writing – original draft; 4. BI: Conceptualization; Methodology; Writing – original draft; Writing – review and editing. 5. MM: Conceptualization; Funding acquisition; Methodology; Writing – original draft; Writing – review and editing. 6. FP: Conceptualization; Funding acquisition; Methodology; Formal analysis, Writing – original draft; Writing – review & editing; 7. UJ: Methodology; Writing – review & 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/fenvs.2021.668836/full#supplementary-material

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Disentangling Challenges to Scaling Alternate Wetting and Drying Technology for Rice Cultivation: Distilling Lessons From 20 Years of Experience in the Philippines

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Alternate wetting and drying (AWD) is a low-cost innovation that enables farmers to adapt to increasingly water scarcity conditions (such as drought), increase overall farm production efficiency, and mitigate greenhouse gas (GHG) emissions. It is seen as a pathway for transforming agri-food systems into more resilient, productive, biologically diverse, and equitable forms, ensuring our commitments to the UN Sustainable Development Goals (SDGs). This paper uses scaling up and innovation uncertainty frameworks to review the success and challenges of AWD's 20-year scaling trajectory in the Philippines and explain the key factors that have influenced its outcomes. The framework adapted for this study is also used to examine the fitness between the scaling context and requirements, organizational mission, and corresponding capabilities. Findings show the innovation platform that vertically integrated key actors and locally adapted AWD has helped foster essential breakthroughs in creating an enabling environment that took AWD to national policy adoption in the Philippines. However, the dominant focus on technology transfer, product focus, and preference for controlled environments in the scaling practice has neglected many important contextual factors, allowing mismatches in enabling policy incentives, institutions, and scale to diminish the impacts of AWD in gravity-based systems. Our findings suggest that rethinking and re-envisioning the ways in which the impact can be scaled in irrigation rice systems using AWD is critical to sustaining food security and making the agriculture sector more resilient to climate change.

Keywords: scaling strategies, diffusion of innovations, impact, climate mitigation and adaptation, innovation systems, water management, system resilience

INTRODUCTION

In any rice-based developing economy, irrigation is a precondition for boosting agricultural production. But rising population, competing water uses among various sectors, and worsening climate conditions make it challenging for farmers to have sufficient water at the right place and at the right time. Agriculture uses ~70% of the planet's freshwater supply (Campbell et al., 2017), of which 40% is used for rice cultivation. As a staple food for half of humanity, more than 3 billion people rely on this crop as their main source of livelihood. Therefore, enhancing rice production—and looking for ways to cultivate it with less water—is essential to assuring global food security. With current practices, rice production not only consume vast amounts of water; it also releases a significant amount of greenhouse gas (GHG) into the atmosphere. An estimated 10% of global agricultural methane emissions are generated by rice production, and its cultivation is second only to livestock production as a source of methane emissions (Tubiello et al., 2014). While globally, rice production contributes only 1.5% of the total anthropogenic GHG, this share is much higher in rice-producing countries (Wassmann et al., 2019).

The Philippine agricultural sector is intricately linked to farm employment and the economy, water use, and GHG emissions. Agriculture is an essential pillar of the economy and is a significant water user in the country, accounting for 73% of the country's total water consumption and second-largest emitter of GHGs, contributing 53.7 $MtCO_2e$ to the national total emissions (FAO, 2018). Annual per capita water availability in the Philippines has been in constant decline due to increased water demand. This results from economic and population growth and decreased water supply associated with the degradation of watersheds and climate change. In fact, the Philippines was rated the second most at-risk nation in 2018 by the 2020 Global Climate Risk Index and has consistently ranked in the top 20 since 2015 (Eckstein et al., 2020). The IPCC 2018 Special Report projects that a 0.5°C increase from the 1.5°C warming scenario will likely result in more severe climate change impacts and associated risks on ecosystems through increased temperature extremes and increased frequency and intensity of heavy precipitation and drought (IPCC, 2018). This is why the agriculture sector is a vital aspect of a country's resilience building; it is not only the most vulnerable in terms of the devastating impacts of climate variability and increasing frequency of extreme weather events, it is also an important sector from the standpoint of mitigating climate change. Seventy percent of the area harvested to paddy rice comes from the irrigated ecosystems of the country, which contribute 77% of the total rice produced (PSA, 2020). Of the total rice area, 3.26 million ha is under the irrigated environment and contributes 77% of the country's total rice production. Clearly, to ensure water and food security, efficiencies in agriculture are required immediately. Rice production practices consume the largest share of water in the agricultural sector because most farmers practice continuous flooding throughout the cropping season. Therefore, optimization of rice production through new management practices that maintain rice yields with greater water-productivity is essential to ensuring the country's food security and access to freshwater for all.

Alternate wetting and drying (AWD), an irrigation scheduling technique for rice production, is a widely researched innovation for adapting agri-food systems to climate change, reducing environmental footprints, and ensuring a resilient and sustainable food production system (Lampayan et al., 2015; Carrijo et al., 2017; Rejesus et al., 2017). Alternate wetting and drying is a low-cost approach that enables farmers to adapt to increasingly water scarcity conditions, such as drought. When properly applied, AWD can increase overall farm production efficiency and mitigate GHG emissions (Rejesus et al., 2014; Valdivia et al., 2016; Allen and Sander, 2019). The Philippines is one of the focus countries where AWD was first piloted and disseminated in the early 2000s. It has been reported that 60% of the Philippine farming area is climatically suited to AWD (Sander et al., 2017). In terms of CO_2 emissions, is estimated that AWD can potentially mitigate 91.2 $MtCO_2e$ within a 2015–2050 timeframe (USAID, 2015). For these reasons, the Philippine Government has taken steps to scale AWD in all national irrigation systems (NIS) and considers the technique a key adaptation and mitigation measure for meeting its Nationally Determined Contributions (NDC) (Arnaoudov et al., 2015), the official country commitment for achieving the goals of the Paris Climate Agreement. It also serves as the basis for long-term public investments and a potential instrument for accessing international climate finance. After two decades of scaling efforts, AWD adoption has been limited and much has yet to be achieved in terms of reaching the farmers nationwide. In 2016, adoption was estimated at 60,559 farmers, covering 84,784 ha of land, which represents <5% of the total irrigated area of 1.86 million ha (Rejesus et al., 2017). There is growing interest from the government and development partners in the scaling out of this technology.

This paper reviews the technological pathways to scaling AWD in the Philippines from 2000 to 2020 and aims to understand the different drivers and factors that influenced and constrained its success. This paper draws on the scaling-up framework of Hartmann and Linn (2008) and Cooley and Linn (2014) and innovation uncertainties framework of Seelos and Mair (2017) to assess how AWD scaling initiatives have interacted with different ecological and governance scales over time. Innovation uncertainty enables an understanding of how the innovation process accumulates and manages knowledge from its experience and use them to inform the potential scaling strategies.

ANALYTICAL FRAMEWORK AND DATA

Analytical Framework

Increasing the scale of adoption of technologies and practices is important for achieving widespread impact. But not all innovations are realized at scale, and if they are, this often happens in varied and context-specific ways. Scaling up spreads the beneficial use of technology, institutional, and/or capacity building practices within and across organizations and networks, from local to regional, national, and global levels (Menter et al., 2004; Millar and Connell, 2010). Scaling out, on the other hand, concerns the geographical expansion of the technology, practice, or systems change over time (Millar and Connell, 2010). Scaling out is often referred to as replication, dissemination, technology transfer, mainstreaming, and rolling out (Wigboldus and Leeuwis, 2013). Scaling deep relates to understanding and influencing cultural, behavioral, and relational contexts that are fundamental to introducing change (Moore et al., 2015). These efforts broadly involve capacity building and transformative learning to shape narratives and norms that are typically sustained through networks and communities of practices.

These are complex processes involving interrelated systems influenced by multiple actors, norms, and cultures (McLean and Gargani, 2019). Scaling tends to involve many interdependencies across actors and various bio-geophysical systems. Scaling out does not occur independently of scaling up/deep or vice versa; these are interlinked pathways that often complement and trigger each other. Scaling to a larger area, e.g., from farm fields to irrigated rice-based food systems, is often associated with greater uncertainty because institutional and contextual complexity grows as system boundaries enlarge (Wigboldus and Leeuwis, 2013). This situation makes scaling an inherently complex pursuit. Similarly, scaling technological innovations requires behavioral, organizational, or institutional change, which is often dictated by the contextual environment. This definition explains the reason transplantation of best practices, with a narrow awareness of knowledge uncertainties and untested assumptions, has been a surprising source of frustration and costly failure when implementing best practices in different geographies and contexts (Andrews et al., 2017; Woltering et al., 2019).

While innovation scaling is an intentional endeavor, it is a non-linear, iterative, and dynamic process that comes with inherent uncertainties. We view scaling as something that should not be understood merely in terms of quantitative metrics, such as adoption and impact. Scaling is also contingent on two outcomes: (i) fitness between the scaling context and requirements and (ii) actors learning to reduce the uncertainties in scaling strategies, which are the cause of failed attempts to scale technologies or practices.

To assess the scaling and adoption challenges of AWD, two frameworks were adapted for this study, namely, the "scaling up framework" (Hartmann and Linn, 2008; Cooley and Linn, 2014) and "innovation uncertainty framework" (Seelos and Mair, 2017; see **Figure 1**). The scaling up framework identifies the innovation, learning, and scaling up cycles as key components or phases that allow us to characterize the broad dynamic and interactive development of scaling pathways. The scaling up process is influenced by the dimension and vision of scale, drivers (forces that facilitate scaling), and spaces (opportunities created or barriers removed to enable scaling), operational modalities, installation of monitoring and evaluation (M&E), and knowledge management (KM) with attention to scaling opportunities.

We complement this with the "innovation uncertainty framework," which identifies contextual factors that influence the success of innovation scaling. These factors are problem frame, adoption, solution development, unintended consequences, alignment with identity, and managerial uncertainty. Our analysis was performed by comparing, in an evaluative manner, the levels of uncertainty (or the lack of accuracy) of assumptions surrounding how scaling AWD would happen and how knowledge is accumulated and managed to decrease uncertainties against the resulting outcomes and impacts. A key hypothesis here is that the conditions associated with these factors are not static or necessarily linear across the piloting and scaling spectrum. Their definition and scope usually change when you move to scaling. Effectiveness of scaling interventions is evaluated based on the responsiveness and capability to adapt to these uncertainties; through productive use of evidence of what works and what does not in what context.

Data Collection and Limitations

This paper draws primarily on secondary data sources and analysis of peer-reviewed articles, project documents and reports, and evaluations. The data covers five major programs/projects in the Philippines that targeted development, piloting, and scaling of AWD technology in the Philippines from 2000 to 2020 (see **Table 1**).

While this review covers a wide range of evidence on AWD scaling in the Philippines, it is by no means complete or exhaustive in terms of the data we think is available. The distribution of data also determined the availability of institutional memory to inform this study. This data gave us a better, though partial, glimpse of the rationale behind the scaling programs, and the associated adaptation of activities along the way.

RESULTS AND DISCUSSIONS

Alternate Wetting and Drying Technology

The early development phase of AWD was initiated in 2000 through IRRI's Irrigated Rice Research Consortium (IRRC). It started as a problem-oriented initiative to respond to farmers' need to meet irrigation requirements despite water scarcity trends. The principle behind AWD draws from the logic of controlled irrigation. Controlled irrigation (CI) is an irrigation scheduling practice in which farmers apply water to their fields for a number of days after the ponded water disappears (Palis et al., 2004). The novel component of AWD involves the development of a low-cost field water tube for monitoring the depth of ponded water and science-based guidance for managing the depth of the water below the surface of the soil to optimize water savings without incurring yield penalty (Bouman and Tuong, 2001; Belder et al., 2004). With the field water tube, farmers can use CI on their fields and monitor the ponded water depth to manage the water levels. To apply AWD, farmers must intermittently flood and dry their plots by maintaining a "safe" threshold water depth of 15 cm (below the surface), except during the flowering stage when farmers must maintain the pond water depth at 5 cm above ground from 1 week before to 1 week after flowering (Bouman et al., 2007).

Alternate wetting and drying technology also holds promise for sustainably linking water use, energy, and food production to deliver water savings at the irrigation systems level. Improving the water productivity at the irrigation system level through the application of AWD can enable water for other sectoral uses such as domestic, industrial, and energy. However, for this to happen, farmers must collectively practice safe AWD within the irrigation scheme. Based on suitability assessment, AWD is climatically suited to more than 90% in the dry and about 34% in the wet season (Sander et al., 2017). This highlights the great potential for technology scaling and adoption in the country.

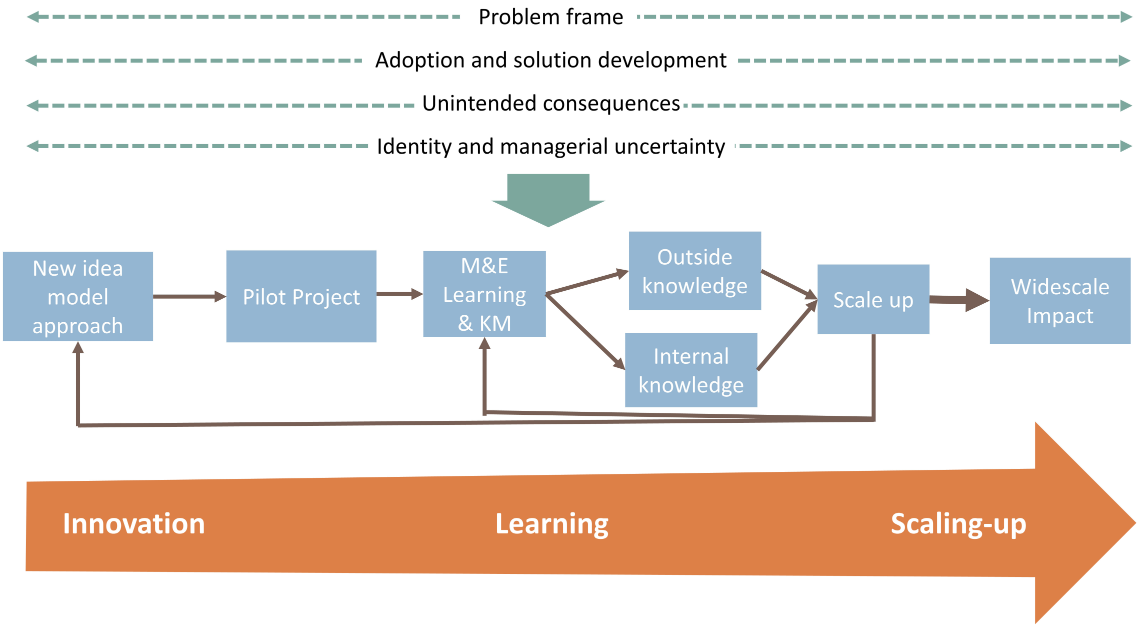

FIGURE 1 | Combined scaling up and innovation uncertainty framework (Adapted from: Cooley and Linn, 2014; Seelos and Mair, 2017)

TABLE 1 | Key projects that developed and scaled AWD technology in the Philippines, 2000–2020.

Project acronym	**IRRC**	**GHG measurement**	**AssoTech**	**AWD IA**	**WateRice**
Period	2001–2012	2010–2012	2013–2017	2016–2017	2017–2021
Area	Region 3 and 7	Region 3	Regions 1–13 and CAR	Region 5	Regions 1, 2, 3, 6, and 12
Interventions	Technology development, farmer field-testing, multi-stakeholder, training-of-trainers	Field experiments, training	Farmer field demo, seminars, training	Randomized controlled trials (RCT), modeling, and FGDs	Technology development and testing, training
Implementers	IRRI, PhilRice, NIA	IRRI, PhilRice	IRRI, PhilRice, NIA	IRRI, PhilRice	IRRI, PhilRice, NIA
Project type	Technology development, adaptation, piloting to scaling up and out	Discovery, Proof-of-concept	Scaling out	Proof-of-concept	Discovery, Proof-of-concept and piloting

Source: Authors.

Economic Benefits of AWD Adoption From Field Trials in the Philippines

We summarize the findings of seven economic studies that have evaluated the benefits of safe AWD from the pilot to replication stages (see **Table** in **Supplementary Material**). Most of these studies conducted participatory field demonstrations and trials in pump irrigation systems (i.e., tube wells) in Region III (Tarlac, Nueva Ecija). A few studies were conducted in gravity canal-based systems in Region V (Camarines Sur) and Region VII (Bohol). These studies employed before and after, with, and without approaches, or both, in which researchers had farmers test the application of traditional irrigation through continuous flooding and safe-AWD practices side-by-side on two plots (Palis et al., 2004, 2017; Sibayan et al., 2010). This approach is also considered an effective demonstration tool for promoting and diffusing the technology because farmers are more likely to test out a technology when they see it for themselves (Hoffmann et al., 2007).

The results of these studies show that the direct benefit of safe-AWD is irrigation water savings. In both pump- and canal-based irrigation systems, AWD reduces water use by 16–28% compared with traditional continuous flooding. Water saving is also associated with a 38–48% reduction in the time farmers require to irrigate their fields. Other potential effects of AWD on water productivity, crop yield, and income were also investigated. However, safe AWD was found to have no significant effect on yield. In terms of income effects, safe AWD increased farmers' net returns in pump-irrigated systems through savings on the fuel costs associated with irrigation of up to 40–46%, or USD 52 to USD 102 per ha. However, in gravity systems, these studies synonymously concluded that AWD has no significant impact on farmers' income. This finding may be due to difficulty excluding unintended users from accessing irrigation systems, even with administrative enforcement of irrigation scheduling. Another reason is that irrigation infrastructure and collective management of the physical and institutional conditions determines the excludability and predictability of water used by farmers (Pearson et al., 2018). In canal-based systems, the reduction in irrigation use by upstream farmers due to AWD adoption has resulted in a more reliable water supply to downstream farmers, which eventually led to improved ability to irrigate their crops (Sibayan et al., 2010; Rejesus et al., 2014, 2017; Valdivia et al., 2016; Palis et al., 2017). From 2005 to 2010, it is estimated that 197 farmers increased the extent of their irrigated farm area on average by 0.2 ha per farmer, resulting in increased production from an average of 377 kg ha^{-1} in dry season and 256 kg ha^{-1} in wet season (Valdivia et al., 2016).

Drivers of Scaling

Throughout the AWD scaling pathway, the relevance of the technology in relation to the policy priorities and mandates of the Philippine Government in the agriculture and irrigation sector was clear and robust. This understanding drove a long-standing partnership and policy support from the Philippine Department of Agriculture (DA) and National Irrigation Administration (NIA).

We looked at various factors that could play a role in AWD scaling pathway. **Figures 2A,B** show how El Niño years have often coincided with stifled rice production in the country. This relationship is found more pronounced in strong El Niño phases characterized by delayed on-set of the rainy season and rice planting, diminished irrigation and reduced harvestable areas (Dawe et al., 2009; Sutton et al., 2019). The **Figure 2C** indicates, however, that price, during these El Niño years, moves independently of the annual rice production levels because of trade and supply side measures at play (Dawe et al., 2009).

The global price spike in 2007–2008, which tripled from USD 335 to over USD 1,000 per metric ton in a matter of 6 months, created immense pressure on the country—where rice is the main staple food—to ensure rice availability and accessibility (Manzano and Prado, 2014). Following the rice crisis in 2008, the DA initiated programs to meet rice productivity targets with limited water resources and dwindling irrigation infrastructure, which led to the launch of its Food Self-Sufficiency Program (Rejesus et al., 2014; Inocencio and Barker, 2018).

Improving water productivity through AWD was one of the solutions used to address these problems upfront. Alternate wetting and drying also offered low-cost solutions without significant investment in irrigation infrastructure and showed great potential to improve water productivity. The technology's proposition together with concerns over the rice price crisis and drought events attracted the interests of government agencies, NGOs, and farmers. This backdrop and the direct relevance of AWD to the DA and NIA mandates provided a firm framework for collaboration between the two agencies and the subsequent integration of AWD into their national programs (Rejesus et al., 2014; Lampayan et al., 2015).

In 2016, with increasing concerns over climate change and commitments for adaptation, AWD technology became a promising option under the government's climate change mainstreaming efforts in the agriculture sector (Arnaoudov et al., 2015). Alternate wetting and drying was proposed as one of the DA's priority adaptation and mitigation measures for the country's NDC. The NDC not only outlines the country's conditional and unconditional commitments to international climate action to limit warming within 1.5–2°C above pre-industrial levels, it also provides opportunities for developing countries to tap into available climate financing to drive transformations toward climate-resilient agri-food systems.

Pathways to Scale

The analysis of this study found that AWD scaling pathways underwent iterative cycles of technological adaptation, promotion, and scaling. These pathways are characterized by the following interdependent mechanisms: (i) multi-stakeholder innovation platforms and adaptive research; (ii) capacity building and participatory dissemination; and (iii) policy support and institutional arrangements. The sequence of activities and scaling outcomes is described in **Figure 3**.

Development and Introduction of Technology Through Multi-stakeholder Innovation Platform

Alternate wetting and drying was developed through a multi-stakeholder innovation platform called the Water-Saving Workgroup as part of the IRRC in early 2000. The network brought together key actors, including national agricultural research and extension systems, farmer irrigation cooperatives, and individuals with a shared vision of spreading knowledge of promising rice technologies to improve farmers' income and productivity (Lampayan et al., 2014; Rejesus et al., 2014; Palis et al., 2017). The working group's main goal was to pilot test and disseminate AWD. The initial participatory adaptive trials were conducted in a pump-based deep-well irrigation system (Palis et al., 2004). Although positive results were observed in terms of irrigation water savings, farmers were apprehensive about some aspects of the logic behind AWD, such as reducing water use and seeing resulting cracked soils, which were a stark contrast to their traditional practice of continuous flooding (Palis et al., 2004, 2017). The technology was also viewed by farmers as both knowledge and labor intensive (Yamaguchi et al., 2019). It required them to tend to their fields more often and follow an established irrigation calendar strictly until harvest (Arnaoudov et al., 2015; Palis et al., 2017). Because of this perception and out of fear of reducing their yields, some of the farmers in the group started to illicitly tap on the irrigation circumventing the agreed arrangements to follow AWD practice (Palis et al., 2004).

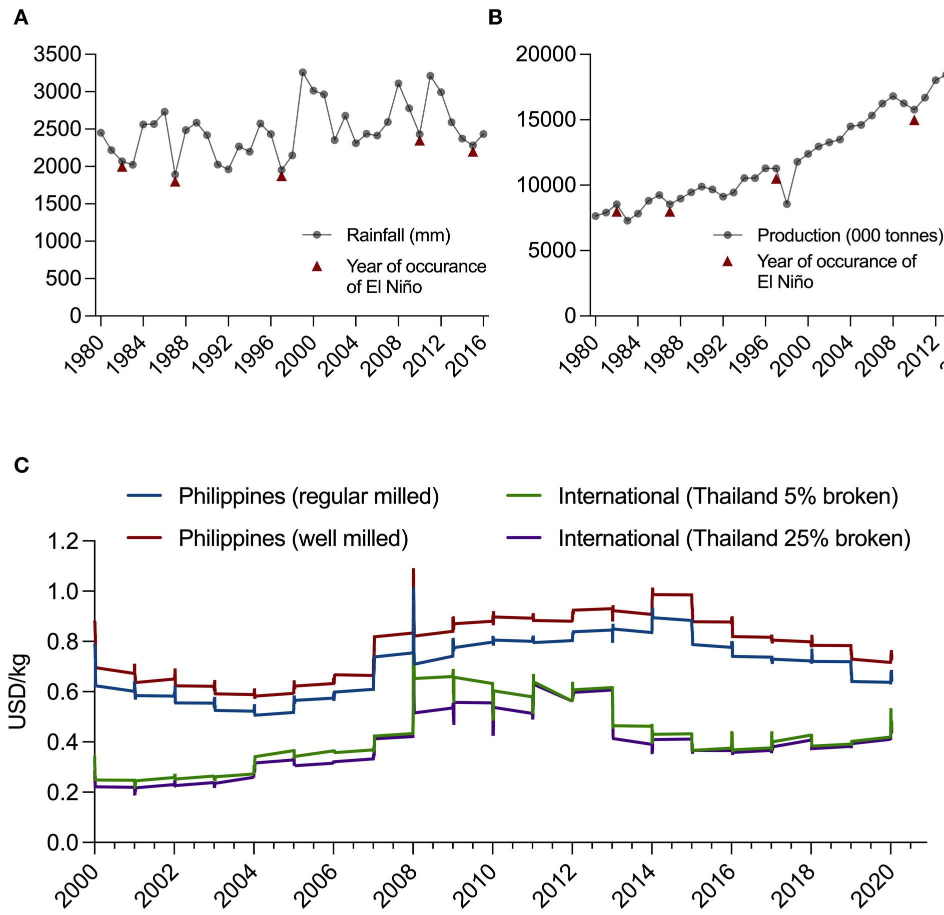

FIGURE 2 | Potential drivers of various AWD initiatives in Philippines including **(A)** rainfall and El Niño cycles, **(B)** total rice production, and **(C)** rice price (Sources: World Bank, 2021; FAO STAT; FAO GIEWS FPMA; IMF-IFS; OCHA, 2015).

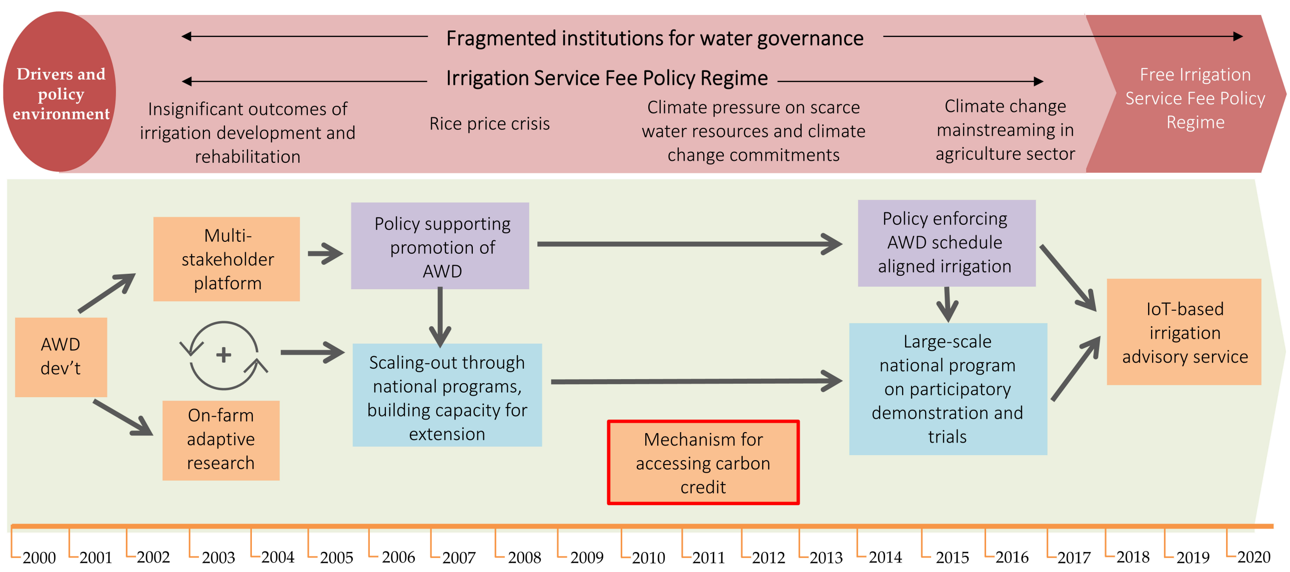

FIGURE 3 | Scaling trajectory of AWD in the Philippines, 2000–2020 (Sources: Authors)

Scaling-Out AWD Through Participatory Demonstration, Capacity Building, and Enabling Policies

To address the challenge of lack of trust and improve scaling out, an incentives-based model to improve adoption was also tested by introducing a payment scheme that internalized the costs of fuel that farmers consume to irrigate their fields (Palis et al., 2004). Along with incentives, the technology was further improved to avoid stress at the critical growth stage, and this technique was called "safe-AWD" (Rejesus et al., 2014). This resulted in increased trust among the irrigation cooperatives (Palis et al., 2017). With greater confidence in the use and benefits of safe-AWD, the irrigators' association decided to diffuse or scale out the innovation to the entire service area of the targeted irrigation scheme (about 72 deep-well systems covering 3,355 ha for 2,256 farmer members; Lampayan et al., 2009; Rejesus et al., 2011). The scaling effort in deep-well pumps also introduced irrigation rotations that intentionally approximated farmer irrigation schedules consistent with the safe-AWD technique.

In the mid-2000s, AWD was tested in gravity-based NIS in the Bohol Irrigation System (BIS) and the Upper Pampanga River Integrated Irrigation System (UPRIIS). National irrigation systems includes large irrigation systems that exceed 1,000 ha, typically ranging from about 30,000–110,000 ha (Clemente et al., 2020). Similar to pump irrigation systems, challenges to convincing the farmers to test the technology were also encountered in the gravity-based system. Similar to experience in other countries like Bangladesh, in this system, there was no associated economic gain for adopting AWD because farmers pay a fixed irrigation fee that is determined by the size of the irrigated area (Arnaoudov et al., 2015; Pandey et al., 2020). The incentive-led adoption model was also tested in the gravity system by guaranteeing compensation for whatever yield loss volunteer farmers might incur by providing agricultural inputs and enough water for irrigation (Sibayan et al., 2010; Regalado et al., 2018). The replication trials were subsequently scaled out in BIS in 2005 (∼4,000 ha) and UPRIIS in 2007 (16,000 out of 82,000 ha) (Rejesus et al., 2014; Lampayan et al., 2015; Palis et al., 2017).

The success of AWD in both pump- and gravity-based systems led to initiation of scaling up efforts through policy support by the DA and NIA, which encouraged the adoption of AWD. In 2009, the DA issued an administrative order promoting AWD as a water-saving measure in its agricultural programs (Rejesus et al., 2014; Palis et al., 2017). This was complemented by training and farmer field school initiatives for about 3,000 trainers, technicians, academicians, and farmers in many parts of the country through local government units (LGUs) and village partners (Rejesus et al., 2014; Palis et al., 2017). In 2016, the NIA issued Memorandum Circular 36 promulgating AWD's adoption in all NISs in the Philippines through irrigation scheduling (Palis et al., 2017). Along with the DA's national efforts, the AWD network membership grew to include national and local state universities, agricultural training and extensions, and LGUs. This platform served as a vehicle for building synergistic interactions and stimulating institutional learning among members and across national borders that helped grow the network, which led to the fast-track dissemination and engendered scaling up of the technology. Alternate wetting and drying scaling out efforts peaked from 2013 to 2017, during which AWD was intensively disseminated all over the country. The scaling program bundled together AWD technology with other income-enhancing technologies, such as drum seeders for row seeding, certified seeds of recommended varieties, and crop managers in large- and small-scale irrigation systems (Regalado et al., 2018). The scaling activities were administered through participatory-cum-demonstration trials.

Scaling Through a Model for Accessing Clean Development Incentives

In 2015, the DA also considered adopting AWD in its flagship program focused on strengthening Adaptation and Mitigation Initiatives in Agriculture (AMIA) as a strategy for the irrigated rice sector, through which it intends to manage 750,000 ha of irrigated fields under AWD (Arnaoudov et al., 2015). Because of its GHG mitigation benefits, AWD was seen as a promising tool for adaptation to and mitigation of climate change and to access carbon credits in the United Nations Framework Convention on Climate Change (UNFCCC) Clean Development Mechanism. The clean development mechanism (CDM) is one of the Kyoto Protocol approaches for undertaking environmentally sustainable activities. A methodology for calculating GHG emissions was developed for accessing carbon-based payments that would create greater incentives for farmers to collectively adopt safe-AWD on a larger scale (Siopongco and Wassmann, 2013). After UNFCCC approval of the methodology in 2011, which did not require the implementers to conduct any GHG measurements to prove farmer compliance, this innovation supposedly simplified adoption of the methodology and made it less costly. However, due to challenges in designing feasible institutional arrangements for carbon-based payment, it did not move beyond the piloting stage.

Scaling Through Integrated Irrigation Advisory Mechanisms

The advent of low-cost sensor technologies provided opportunities for improving AWD adoption. This primarily provided a way to address AWD farmer adoption challenges, knowledge, and labor, the unreliability of water supply result in a mismatch of the timing AWD, and, inefficiencies in coordination and water management across administration (Regalado et al., 2019). The outcome of this learning was the development and piloting of AutoMon^{PH}, an Internet-of-Things-(IoT)-powered decision support tool that provides irrigation advisory service to farmers and irrigation managers (IRRI and PhilRice, 2020), making it easier to adopt AWD, efficiently manage water demand and delivery, and ultimately, sustainably manage water resources. This technology is being benchmarked in different irrigation contexts, from irrigation systems with relatively good water control (pump-based) to gravity-based systems where collective action is required for managing the water. However, the AutoMon^{PH} based solutions is still at a concept validation stage and haven't generated any evidences of scaling of AWD.

Binding Constraints to Impact at Scale

Even though there is some evidence of AWD scaling in small-scale systems and demonstration of it in large-scale irrigation systems, there is a growing mix of evidence suggesting that the long-term impacts of AWD are minimal. In terms of reach and adoption of AWD, there is data available detailing several years its use. However, the available studies were done independently and have different measurement approaches, which are not substantive enough to provide a systematic picture of the adoption but nevertheless offer a useful starting point to provide some indication of the trends. In the early stages (2002–2004), AWD piloting was estimated to have reached a cooperation level of 3,355 farmers, and this number increased to 20,000 from 2005 to 2007 during the scaling out (Rejesus et al., 2014; Palis et al., 2017). Adoption of AWD increased from 93,014 farmers in 2011 (Dixit et al., 2016) to 140,000 in 2013 (Arnaoudov et al., 2015), and decreased to 84,784 in 2016 (Rejesus et al., 2017).

This study analyzed the existing evidence to assess how assumptions on which scaling interventions are based capture sufficient knowledge about areas of innovation uncertainties (see **Table 2**).

Framing Problems From a Techno-Centric and Unidimensional Perspective

Water scarcity is a multifaceted issue, and this certainly applies to irrigation systems to most of the countries (Breen et al., 2018). This definition gives the backdrop opportunities to address irrigation water scarcity through efficient irrigation technologies and practices, becoming the entry point for scaling AWD technology. The rationale for scaling AWD is based on a problem definition of prevalent irrigation water scarcity, driven to extremes by climate change conditions, that affects farmers and which could be addressed if not for the lack of access and the capacity to apply the technology.

Framing the problem in this way, however, is techno-centric and uni-dimensional, and it assumes that scaling AWD can be achieved if farmers decide to adopt it and have the technical know-how and skills to apply the AWD technique (Breen et al., 2018; De Loë and Patterson, 2018; Glover et al., 2019). Scaling strategies that exemplify this have been largely characterized by information sharing, training, technology demonstrations, and transfer. While adoption of AWD does indeed concern individual farmers, scaling AWD goes beyond the level of the individual, and the problem of irrigation water involves causes that are much deeper than lack of water. The intentional shift from piloting to scaling also enlarges not only the geographical scope but also its systems of interest. Moving to scaling in irrigation systems not only involves individual farmers' decisions, but also incentives for adoption and cooperation, and adequate management and sufficient quality of irrigation systems are necessary conditions. Therefore, scaling goes beyond individualistic factors to include the institutions and systems that ensure the social and technical conditions necessary for irrigation provisioning, such as irrigation infrastructure, institutional arrangements for irrigation water allocation and enforcement, water pricing systems, and monitoring and enforcement (Araral, 2009; Schut et al., 2020).

Fragmented and multilayered institutional arrangements coupled with a weak capacity to enforce policies characterize the governance regime for water in the Philippines (Rola et al., 2018). There is no central planning body for water in the country. Instead, the mandate for governing water is spread over multiple water institutions. Specific to irrigation governance, there are at least 13 national agencies that have irrigation-related functions or mandates (Rola, 2019). The irrigation governance landscape is currently mired with overlaps and redundancies that result in uncoordinated planning and development of irrigation systems. For example, irrigation master planning and development are undertaken by the NIA and the Bureau of Soils and Water Management (BSWM). The Department of Environment and Natural Resources River Basin Control Office (DENR-RBCO) also has its own master plan for river basin management, which has identified potential irrigation development sites. Moreover, the NIA is also responsible for water use management and watershed management in areas where large irrigation systems are located; this is also the mandate of the DENR forest management bureau and the National Power Corporation which governs hydropower. However, due to the lack of human resources as a result of the rationalization of its staff, the NIA could not adequately perform its watershed management functions (Rola et al., 2020). The quality of irrigation service provisioning and water quality can also be attributed to weak institutional enforcement and governance issues (Clemente et al., 2020). Shortages of downstream irrigation are often caused by unabated illegal access and locking of gates, illegal settlers, pumping/dumping of garbage/turnouts, and poor canal maintenance.

Farmers not only experience water scarcity, but because of increasing climate variability, they also suffer from the extremes of both poor water availability in dry season and flooding in wet season. The most common water supply problem is water shortage during the dry season. In the dry season, irrigation associations implement remedial measures such as construction of re-use dams and shallow tube wells. They also implement AWD as a coping mechanism rather than being a deliberate decision to adopt AWD to improve water productivity and increase irrigation availability downstream—similar to the findings in Zhange Irrigation System (Mushtaq et al., 2006). During the wet season, some major systems suffer from flooding which limits cropping to dry season (Clemente et al., 2020). Excessive siltation in dams and canals is also a major problem in large irrigation systems; in some areas, an 8-m wide main canal may be reduced to 1-m, thus reducing the available irrigation water supply (Clemente et al., 2020). The literature points to these factors as an explanation of why, despite considerable investment in irrigation development and rehabilitation—accounting for a third of the total expenditure in agriculture since the 1960s—the levels of cropping intensity over the years have not significantly improved (Delos Reyes, 2017).

Limits of "Technology Push" to Scaling

Two essential conditions for scaling AWD technologies are whether farmers are willing to adopt them and whether the required operational and environmental conditions are in

TABLE 2 | Overview of AWD scaling strategies (thus far) and gaps.

Innovation uncertainties	Findings of the review	AWD scaling assumptions and interventions	Analysis of scaling gap
• How is the problem of irrigation understood?	• Poor irrigation management is caused by multiple factors: poor water governance and management, poor irrigation infrastructure or water delivery systems, and non-compliance toward institutional arrangements. • Poor irrigation development and management results into dwindling quantity and reliability of irrigation supply.	• Presence of and climate-induced irrigation water scarcity are seen as main causes of low irrigation. • Technologies or practices that increase water productivity are considered a stand-alone solution to addressing irrigation water scarcity. • Practicing AWD can increase availability of irrigation water and thereby crop intensity and irrigation coverage.	• There appears to be a problem with framing and sufficiency solution mismatch, particularly in gravity-based systems. • AWD is only partially effective in resolving water scarcity in irrigation systems experiencing declining irrigation infrastructure quality and unreliable quality of irrigation provisioning.
• How are the facilitating and hindering factors to farmer adoption of AWD understood?	• AWD is a knowledge-intensive technology and its logic contrasts with traditional irrigation. • Adoption of AWD is non-binary. • AWD does not affect yield, but it can increase farm irrigation coverage. • Economic incentive exists to adopt AWD in pump irrigation systems. • Strong institutional enforcement is key to AWD adoption in canal-based systems.	• Participatory field trials, with a guarantee of compensation for yield loss, were taken as an approach to addressing the initial apprehensions of farmer cooperators and are coordinated through the farmer associations. • Purposive selection of volunteer farmer cooperators, with conducive farm conditions, in field trials of AWD helped control for context variability in farm irrigation contexts.	• Factors of farmer adoption are known, but there is a lack of knowledge about how to make AWD scaling work in contexts beyond controlled favorable field trial conditions. • While institutional enforcement is an important mechanism for adoption, this knowledge does not feature as a major component of AWD scaling strategy.
• How are requirements for successful scaling of irrigation development and management impact understood?	• Adequate irrigation infrastructure is necessary for scaling AWD. • Public institutions lack adequate capacity and resources for extension and monitoring of AWD. • Water pricing scheme determines the incentives for farmer adoption of AWD and compliance to institutional arrangements.	• Scaling strategy focused on increasing geographic coverage through participatory demonstration and information dissemination. • Suitability analysis is available for targeting and prioritizing areas for scaling AWD in the country; this study used soil quality and climate information as criteria for suitability. • Mainstreaming of AWD through the DA and NIA policy and programs promoting the technology to the farmers.	• AWD scaling strategy is limited and does not address other key scaling concerns and new challenges brought about by FISA. • The suitability analysis does not consider the institutional and infrastructural characteristics of irrigation systems, which are far more critical as determinants of whether AWD can be scaled-out successfully.
• What are the unintended consequences and trade-offs related to the use of AWD?	• AWD adoption is interdependent with other livelihood and water use systems. • Benefits, trade-offs, facilitating/hindering factors, unintended consequences of AWD adoption happen at different scales.	• The farmer irrigation dynamics in pump irrigation systems were well-studied, to some extent; cross-sectoral interactions with different actors and sectors were explored. • Farmer-level and sector-level trade-offs were explored.	• Knowledge of the trade-offs and cross-scale concerns of AWD adoption is explored but has not been translated into strategy and operation of scaling theory of change. There is still insufficient understanding of the cross-scale tradeoffs of AWD.

Source: Authors.

place for AWD adoption at scale. The main scaling approach undertaken with AWD technology has been dissemination integrated with participatory technology demonstration trials. National partners played an important role in promoting and diffusing the technology through farmers' field days and demonstration visits. Like many other natural resource management practices, AWD technology is knowledge-intensive (Yamaguchi et al., 2019). Its adoption is not straightforward or binary when compared with other crop management practices (Sumberg, 2016; Glover et al., 2019). Alternate wetting and drying application lies along a spectrum of consistency in the management of subsurface water levels within safe thresholds. This work not only requires farmers to monitor water levels and corresponding irrigation adjustments, but also reliable water supply (which depends on a functional water governance structure).

Farmers are risk-averse in terms of testing AWD technology because the logic behind how the technology works starkly contrasts with their traditional practice of continuous flooding. While AWD can improve irrigation crop intensity and total productivity, AWD does not directly impact yield improvement, particularly for gravity-based irrigation systems, However, participatory field demonstrations have shown that AWD has been successfully adopted in pump-irrigation systems where farmers experienced the input cost savings from fuel expenses (Palis et al., 2004; Regalado et al., 2018). This shows the importance of predictability and the ability to exclude unintended users from consuming water resources, and presence of an institution for access rule enforcement (Araral, 2009). However, it is important to note that the coverage of pump-irrigation systems in the country is minimal at 12% and (Delos Reyes, 2017) and the largest share (75%) of farmers in irrigated ecosystems are still using gravity-based systems (Inocencio et al., 2020). In gravity-based irrigation, adoption of AWD has been extremely limited. In the early stages of technology development, it was hypothesized that adoption of AWD in a gravity-based system would result in savings on irrigation fees. In 2017, the irrigation water pricing scheme was revised with the introduction of the Free Irrigation Service Act (FISA). Free Irrigation Service Act removed NIA's revenue from irrigation fees since it is now subsidizing irrigation fees for smallholder farmers with farms of 8 ha and less. This policy may potentially have created a disincentivizing effect in terms of the NIA's motivation to improve its rehabilitation and irrigation system quality and performance (Briones et al., 2019). The multiplicity and conflicting nature of the objectives beset the current mandate of NIA.

The ability to exclude users, enforce compliance mechanisms and water pricing is much clearer in pump-based irrigation systems. Large canal-based systems are highly prone to illegal water tapping, and compliance is much difficult given the scale of the irrigation system. Most of these irrigation infrastructures are already 30–40 years old and are affected to varying degrees by deterioration, siltation, and damage (Clemente et al., 2020; Inocencio et al., 2020). Other challenges related to infrastructure include inadequate head control structures, misplaced and inappropriate flow control and off-take structures, direct off-taking of farm ditches from main canals, inadequate protection of sluice gates and main takes from siltation and very high service-area-to-farm-ditch and turnout ratios. In addition, unreliable estimates of water demand stem from a lack of data and a lack of capacity to measure and determine key water balance requirements, for instance, some of the water supply data available at NIA study site were as much as 50 years old (Rola et al., 2020).

Moreover, there are no updated and interoperable databases or data collections to support real-time decision-making for water resources, conflicts, and enforcement of various water-related laws (Hall et al., 2015). The M&E of irrigation system performance rest with the NIA and BSWM through the DA's respective regional field office. The conduct of M&E is weak, and it significantly lacks human resources along with the application of innovation tools, despite the availability of modern technologies like GIS (Rola et al., 2020). Currently, there is one technical officer per 2,000 ha of irrigation area. These problems cripple coordinated planning, implementation, and M&E of irrigation development and management, which are crucial factors for AWD if it were to be adopted and administered system wide. Several adoption studies provide a good understanding of the constraints and opportunities for scaling AWD. However, these experiences were studied in field trials where farmers were pre-selected based on the favorability of the irrigation infrastructure and their willingness to try AWD. Using AWD is not possible in irrigation systems that do not have flow control structures (Delos Reyes, 2017). Moreover, the major problem of declining infrastructure quality, despite investments and rehabilitation efforts, is a significant uncertainty in terms of AWD's widespread use (Le Loan, 2020; Totin et al., 2020).

These findings suggest great uncertainties surrounding AWD's compatibility with widespread adoption in large-scale irrigation systems unless the entire institutional and irrigation infrastructure ecosystem is considered and enhanced (Shilomboleni and De Plaen, 2019; Schut et al., 2020). These constraints have yet to be adequately addressed in recent scaling efforts, which are still dominated by technology transfer-oriented approaches.

Trade-Off and Cross-Scale Issues

What makes taking AWD to scale in large irrigation systems more challenging is the different cross-scale issues and trade-offs that arise. Since water saving is tied to how water is reallocated, collective participation in adopting AWD in large systems involves a wider range of stakeholders and resource use systems.

Figures 4A–F show a series of graphs depicting the relationships and trade-offs of AWD adoption and their impact on different variables or outcomes. An increase in AWD adoption area generally results in increased savings in the irrigation amount (**Figure 4A**), which can be used to maximize the irrigated areas (**Figure 4B**). These irrigation benefits positively influence income and total productivity. Influences on income have more direct effect in pump irrigated than canal systems. Farmers relying in pump-based irrigation can save almost half of its fuel costs when they properly apply AWD. **Figure 4C** illustrates the trend of reduction in fuel consumptions for pumping water as the AWD adoption area increases.

On the other hand, AWD can increase weed density (**Figure 4D**) if farming practices are not coupled with appropriate weed management interventions (Brim-DeForest et al., 2017; Samoy-Pascual et al., 2020). Some studies done in Nepal reported that AWD restricts the proliferation of weeds due to its soil contraction effects (Howell et al., 2015). While we describe the generic agronomic responses of AWD, these trends may vary with diverse agro-environment. Thus, there is a non-linear relationship between AWD and yield, water productivity and income. There are soil type and crop management factors that also contribute to yield performance, e.g., variety, nutrient, weeds, and pest management (Lampayan et al., 2009; Tirol-Padre et al., 2018). In terms of mitigation benefits, the AWD results in significant reductions in methane emission (**Figure 4E**). However, the degree of reduction decreases with an increase in the area under AWD. Many plots within the rice landscape remain flooded when other plots might be dried to the extent of scheduling irrigation based on AWD. This connotes the spatial variability effect on gains in methane reduction. At the same time, researchers

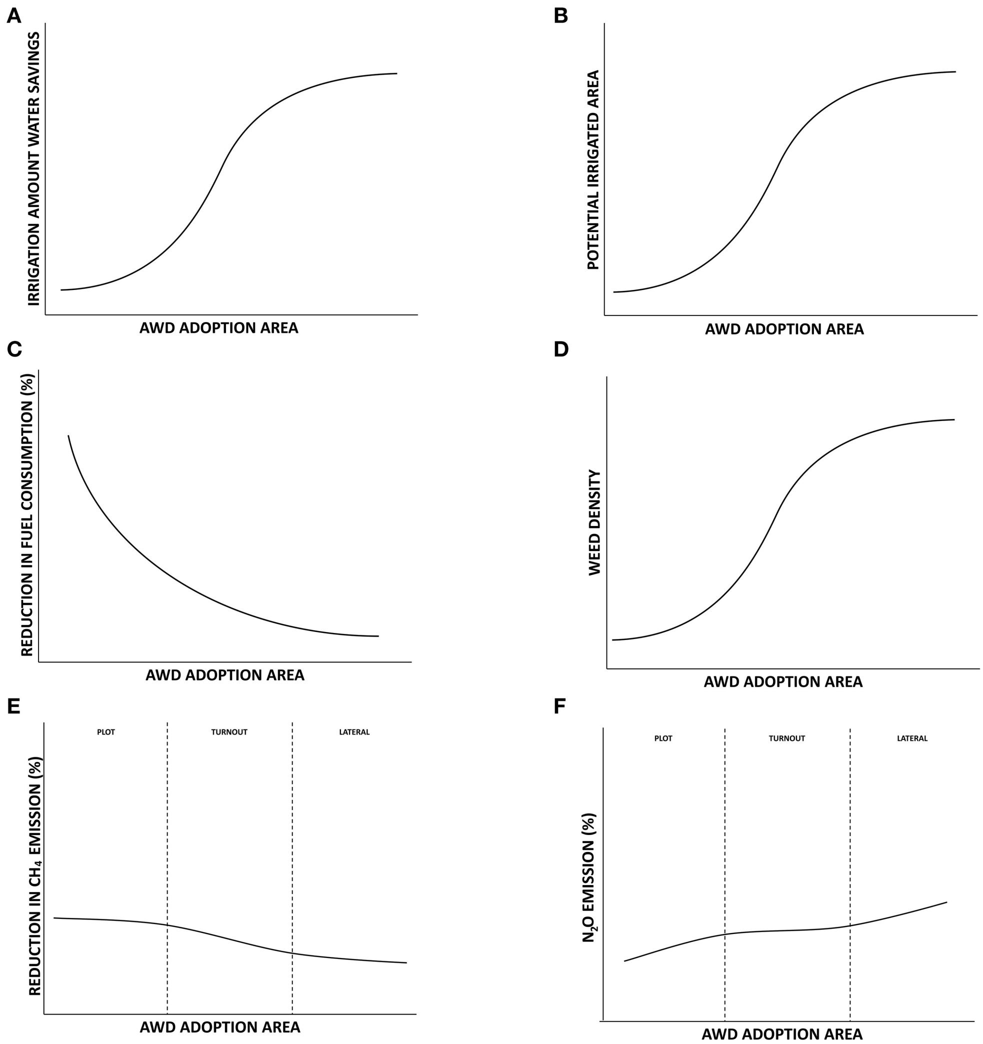

FIGURE 4 | Synergies and trade-offs in AWD adoption by **(A)** irrigation amount savings, **(B)** potential irrigated area, **(C)** reduction in fuel consumption, **(D)** weed density, **(E)** reduction in methane emission, and **(F)** nitrous oxide emission. Graphs represents the generic trend and the responses may vary with diverse agro-environment (Sources: Authors).

found that AWD's mitigating effect on methane can be off-set by nitrous oxide increases (Sibayan et al., 2018) (**Figure 4F**). However, this results in no significant difference in the total global warming potential between AWD and continuous flooding.

At the irrigation community level, the decision to participate in the collective adoption of AWD is a trade-off in itself. The adoption of technology by upstream farmers means that they take risks or forego a higher probability of achieving better productivity by allowing downstream farmers to benefit from more irrigation. This is why participation and community-based engagement are crucial for AWD to benefit farmers. However, results can be exponential. Achieving more equitable water supply among the farmers on the upstream-downstream continuum of canal irrigations is the most practical social benefit of successful AWD adoption. It has been shown to provide downstream farmers with yields that are comparable to farmers higher in the toposequence (Valdivia et al., 2016). Through more reliable water and the potential for improved irrigation coverage, successful AWD adoption has been observed to reduce resource conflicts and stimulate trust among farmers (Sibayan et al., 2010; Rejesus et al., 2014; Palis et al., 2017). The presence of an intense collective action to adopt AWD was a critical mechanism that reflected successful pilot and scaling initiatives in both irrigation systems (Palis et al., 2004, 2017; Lampayan et al., 2009; Regalado et al., 2018).

At the systems level, the issue of siltation, primarily caused by rapid degradation of watersheds located at the upstream end in national systems, is significant. Poor watershed conditions increase the risk of erosion and river siltation, reducing the storage capacities of dams and canals and resulting in decreased availability and reliability of irrigation water, especially for downstream farmers. Addressing this challenge has been difficult due to governance issues. The management and rehabilitation of watersheds are largely within the purview of the DENR and local governments and the planning and implementation of these efforts are often not coordinated with the NIA (Clemente et al., 2020). In a few reservoir-based gravity systems, fishers were some of the non-farm stakeholders affected by AWD adoption (Rejesus et al., 2017). Fish cage operators, whose operations are on lakes that serve as irrigation system reservoirs are highly dependent on lake water levels for their livelihood. They stand to benefit from improved conservation through AWD application, which minimizes the chance of fish kills triggered by low water levels. Alternatively, fish pond operators located in the upper and middle portion of the irrigation system are inversely affected by limited irrigation use, as they continuously need water to fill their ponds to avoid fish mortality. Scaling AWD irrigation system-wide must consider and balance its effects on fisherfolk to prevent negative consequences.

Alternate wetting and drying's success in enabling carbon financing through the CDM failed to flourish as a result of several techno-economic and institutional bottlenecks that deterred its scalability (Siopongco and Wassmann, 2013). First, there are high transaction costs and capacity requirements for farmers venturing into the mechanism, such as accessing the institutional mechanism, monitoring, reporting, and verifying and claiming payments. These may only be viable through a collective organization of farmers or a cooperative at the landscape level in order to take advantage of economies of scale to reduce transaction costs and institutional mechanisms for verification and access to financing (Siopongco and Wassmann, 2013). This also requires farmers to learn new knowledge and capacities to access carbon finance. Second, as carbon prices could fall below USD 1 per ton of CO_2 equivalent, the potential economic returns of the CDM for farmers may not be significant enough to incentivize farmers (Siopongco and Wassmann, 2013). Third, while AWD can drastically reduce irrigation water use and the GHG emissions of farmers, in most cases, the water saved would be used to expand the size of the area irrigated for rice or new crops in future seasons. This means reduced emissions could be off-set by emissions created through newly irrigated land. Ironically, if the water saved is channeled to other sectors, such as urban use, it could be certified as an emission reduction due to a net reduction in global warming potential within the agriculture sector (Wassmann, 2010). This displays the need to think about the various tradeoffs of AWD and its potential as an entry point for water-energy-nexus work.

Lastly, there is potential for system-level benefits of AWD adoption, but it is not yet clear whether these have already been attained because AWD has yet to be implemented system wide in an NIS. To date, only one study attempted to rigorously evaluate AWD's effect on sub-system levels (Rejesus et al., 2017). It is hypothesized that implementing AWD at the NIS level would allow savings from water efficiency gains to be redirected to other sectors such as power generation. Case studies in UPRIIS and RIIS, which are also located on river basins and watersheds, revealed that water savings in irrigation do not significantly benefit the power sector for two reasons (Rejesus et al., 2017). First, the water volume that flows in the irrigation canals is also the water used for power generation. Second, the power companies tap water by accessing it at the source, the dam and lake. These water bodies are not affected by water efficiency gains from AWD adoption, which happen further downstream.

Alternate Wetting and Drying Potential and Challenges in Global Context

Many studies conducted in various countries have shown that AWD can reduce both GHG emissions and irrigation water use. A literature search conducted on the Web of Science for articles published from 1975 to 2021 with the keywords "alternate wetting and drying" and "rice" in the title generated at least 100 articles based on work done mostly in Asia. However, using other common terms like control irrigation, intermittent irrigation, and so on, may generate more than 1,000 published articles. Most of these publications focus on plant response to water deficit in terms of genetic, physiological, and agronomic characteristics and GHG emission. The meta-analysis done by Carrijo et al. (2017) using 56 such studies indicated mild yield penalty (5%) to no effect on yield and a potential irrigation water savings of 23%. However, there are very few studies that confirm the effects of continued use (or expansion of coverage area). Lampayan et al. (2015) reviewed the adoption and economics of AWD in the Philippines, Bangladesh, and Vietnam and concluded that the technique had a high rate of return, with a benefit-cost ratio of 7:1. Despite this, there have been no published reports on large-scale adoption of AWD in these countries. Though many studies have indicated great potential for AWD under small-scale irrigation systems, Pandey et al. (2020) argued that the lack of economic incentives to save water has been a major constraint for large-scale adoption in countries like Bangladesh, where groundwater is used for irrigation in 79% of the total irrigated area. The meta-analysis done by Yagi et al. (2020) based on 31 region-specific studies from five South East Asian countries indicated a potential of 35% reduction of methane emission with AWD. Like Philippines, many Asian countries including Vietnam, Bangladesh, etc., have considered AWD as the priority mitigation option as part its intended NDC to the UNFCCC (Amjath-Babu et al., 2019; Escobar Carbonari et al., 2019).

The analysis and argument made in this study of the Philippine experience applies to most Asian countries where irrigation access is not directly controlled by farmers. The hierarchy of water governance for surface irrigation is similar in most of the Asian countries. In general, irrigation water is either free or water pricing is based on per unit area irrigated, not on the amount of water used. Most smallholder farmers in Asia have fragmented and scattered land holdings, and the plots located within the command area of the sluice gate or pump generally belong to a number of farmers. It is not possible for farmers to apply irrigation based on the drying pattern of each plot. One of the pre-requisite for the adoption of water-saving technologies is an efficient irrigation infrastructure which can promote trust among farmers that they will be able to access the right volume of water at the right time. The benefits of AWD will not be realized in absence of assured irrigation scheduling.

CONCLUSIONS AND RECOMMENDATIONS

Through the lens of innovation uncertainty, this review analyzes how scaling interventions have dealt with knowledge uncertainties surrounding the adoption and benefits of AWD in various irrigation systems, how trade-offs occur across agroecological systems and governance scales, and how these interactions unraveled cross-scale and cross-level issues that ultimately mitigate the resulting outcomes and impacts. The results show that AWD scaling efforts underwent iterative cycles of technological adaptation, promotion, and scaling. This trajectory is characterized by interdependent mechanisms including (i) multi-stakeholder innovation platforms, (ii) participatory technology adaptation and transfer, (iii) capacity building for research and dissemination, and (iv) evidence generation and communication.

Alternate wetting and drying's early phases (2000–2010) involved a synergistic deployment of a multi-stakeholder platform and participatory technology testing, adaptation, and transfer. These mechanisms provided vertical and horizontal linkages that facilitated communication of evidence and institutional uptake by the Philippine Department of Agriculture and various stakeholders. From 2011 to 2020, the country adopted new scaling pathways, including an institutional mechanism for accessing carbon credit and nationwide participatory demonstrations and trials for disseminating AWD. The carbon credit mechanisms did not flourish due to high transaction costs and trade-offs that occurred across the scale. The wide-scale participatory demonstration was also complemented by a policy issuance aligning irrigation scheduling of canal-based irrigation systems with the AWD schedule. In the later stage, learning from AWD's scaling experience culminated in the development of an IoT-powered decision support tool that provides irrigation advisory service to farmers and irrigation managers, making it easier to adopt AWD, efficiently manage water demand and delivery, and ultimately, sustainably manage water resources. This technology is being benchmarked for applicability in different irrigation contexts.

From the two decades of experience scaling this technology, several constraints to scaling AWD were rooted in the heterogeneity of irrigation contexts that were not anticipated in scaling strategies and the trade-offs that occur when AWD adoption and management reach cross-level and cross-scale. Alternate wetting and drying was found to be successful in small-scale pump-based irrigation systems. However, thus far, the scaling experience with large gravity-based systems has been mostly unsuccessful. The study reveals that several factors influence the scalability of AWD. These are economic incentives, institutional enforcement, excludability of access to unintended users, and quality of irrigation infrastructure. Conditions on these factors were more scale-fit in small-scale pump-based irrigations. However, scaling AWD in large gravity-based irrigation systems is comparably more complex and confronts challenges underpinned by scale mismatches. These constraints cut across institutional enforcement, policy regimes and incentives, management and regulation, and the trade-off of benefit streams across livelihood and spatial scales. Given that most irrigated rice-growing areas are in gravity-based irrigation systems, this explains why AWD's impact is largely abated.

Reflecting on the AWD scaling pathway pursued in the last two decades, the study finds that the dominant focus on product-orientation and technology transfer, and preference for controlled environments has neglected many of the important contextual factors, enabling policy incentives, institutions, and scale sensitivities that mitigated the impacts of AWD. The review's findings point to the importance of rethinking the boundaries and assumptions of scaling theory of change for AWD; this requires proper consideration of the institutional and irrigation systems. There is a scaling gap in understanding and learning the contexts in which AWD could be successful and what it will take to succeed in most gravity-based irrigation systems. Much of this requires exploring these uncertainties; being open to failure, which is expected at least in the short term; and moving beyond scaling strategies driven mainly by technology demonstration of AWD in controlled field conditions.

In order to be more impact-oriented, it is necessary to reframe scaling theory to make it more relevant to farmers' needs, including revenue generation and enhancing resilience to climate change. Addressing the problem of irrigation water must not solely focus on water efficiency, but also on ways of ensuring irrigation to farmers at all times. This shifts the focus from farmer-level water management to consider the entire system of irrigation water provisioning, where the capacity of the irrigation systems to monitor and inform water management decisions properly and ensure availability and flexibility of irrigation water is a critical change mechanism. Thus far, researchers have generated enough evidence on the field-level impact of AWD; it's time to look more broadly at opportunities that will trigger wide-scale adoption at the irrigation system scale to achieve significant irrigation water savings and reduce the carbon footprint.

AUTHOR CONTRIBUTIONS

YE and SY contributed to conceptualization and methodology. YE conducted formal analysis. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

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frontiers in Environmental Science

REVIEW
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Covid, the Environment and Food Systems: Contain, Cope and Rebuild Better

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The objective of this paper is to analyse impacts of COVID-19 on the nexus of food systems, the environment and sustainable development and propose ways for governments and international agencies to mitigate impacts in the short and medium term. It covers the historic period from early 2020 to early 2021 and also makes an assessment on future prospects. Although evidence is collected from all around the world, the focus is primarily on developing countries. The methods used are a review of the announced actions and preliminary findings in the academic and grey literature as well as on reliable websites from global and international institutions. By October 2020, governments around the world had invested about $12 trillion to counteract the economic effects of COVID-19. This investment could contribute to progress on the SDGs and global climate targets insofar as it was invested within a framework that supports both socio-economic recovery and sustainability. Initial analysis indicates that investments for economic recovery did not sufficiently address food security and sustainability, concentrating instead on immediate economic risk management. The global sustainable development agenda must promote the resilience and sustainability of food systems through policies and measures that: i) account for environmental thresholds and trade-offs; ii) promote food security and healthy diets; iii) enhance and protect rural livelihoods; and iv) address the inequalities and injustices that have emerged and will prevail during a post-COVID transition. National stimulus programs and the actions of international agencies must be assessed and monitored to deliver multiple benefits simultaneously and guide building back better.

Keywords: COVID-19, food systems, environment, pollution, rebuild

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INTRODUCTION

COVID-19 presents an unprecedented global health and economic crisis. Since detection of the virus at the end of 2019, it has caused around 157 million infections and more than 3.3 million deaths.[1] All around the world, millions of people have lost jobs and income in the deepest economic downturn in living memory. The health impacts include both the direct consequences of infection and the effects

[1]WHO Coronavirus Disease (COVID-19) Dashboard | WHO Coronavirus Disease (COVID-19) Dashboard, Accessed May 10th, 2021.

of measures taken to contain the outbreak, such as increased poverty, hunger, undernutrition and social disruption. These have not yet been fully understood or quantified.[2] It is clear, however, from the material reviewed in this paper, that the combination of economic and health effects is still impacting and will continue to impact the environment. While there are some positive impacts, the majority are negative. Moreover, it is curtailing the prospects for achieving the Sustainable Development Goals (SDGs).

This article analyses the effects of COVID-19 on all aspects of the environment, with a focus on interconnections between the pandemic and the agri-food system and considers how these effects are best mitigated. The findings are highly relevant to the continued response to the pandemic, as well as to prevention of similar crises in the future.

Prior to COVID-19, the case for systemic change in food systems was gathering momentum as countries, the United Nations, and academia drew attention to the role such systems played—both positive and negative—in achieving the SDGs. More than any other sector, the agri-food system entails a web of feedbacks between ecosystems, livelihoods, economic development, trade relations and human health. This means it can support or hinder progress towards many of the 17 SDGs, such as Zero Hunger (SDG 2), Good Health and Well-Being (SDG 3), Gender Equality (SDG 5), Decent Work and Economic Growth (SDG 8) and Climate Action (SDG 13). Food production is a leading driver of biodiversity loss and a major contributor to GHG emissions (PBL Netherlands Environmental Assessment Agency, 2014; Mbow et al., 2019). The food and agriculture sector employs over a billion people world-wide (Food and Agriculture Organization of the United Nations, 2016, p. 18). Food systems are the backbone of human health but also contribute to some of the fastest growing health problems—non-communicable diseases (NCDs) such as diabetes, obesity related cancers and heart disease (World Cancer Research Fund International, 2014; Anand et al., 2015; Food and Agriculture Organization of the United Nations, 2016).

The article is structured as follows. *Macroeconomic Impacts of the COVID19 Crises* lays out the socioeconomic impacts of COVID-19, as well the broad economic impacts measures that alleviate the negative effects of the pandemic. It examines the implications for the food system and food security outcomes. The impacts of the pandemic on the environment and natural systems are evaluated in *Impacts of COVID-19 on the Nexus Between Agri-Food Systems and the Environment*. *Coping Strategies and Their Impacts* looks in detail at what governments are doing in their responses and how these affect the agri-food system as well as the environment. *Lessons From Coping With COVID-19 and the Way Forward* describes what has been learnt so far from government responses and makes recommendations for actions in the short and the medium term. Overall conclusions are in *Conclusion*.

[2]A first overview of impacts based on household surveys can be found at https://advances.sciencemag.org/content/7/6/eabe0997

MACROECONOMIC IMPACTS OF THE COVID19 CRISES

Impacts on GDP Growth and Other Indicators

The negative economic effects of COVID-19 and the measures taken to fight the pandemic have both been enormous. Preliminary estimates by the IMF for 2020 are that a decline in global GDP of 3.5 percent has taken place (International Monetary Fund, 2020b). Such a decline is unprecedented in the postwar period and has had major impacts on poverty, hunger and other key indicators of wellbeing. A recovery is projected for 2021 and 2022, but with exceptional levels of uncertainty, especially given the persistence of infection rates and emergence of new variants of the virus. Even if these challenges are overcome the consequences of COVID-19 will remain for some time. As the World Bank notes, "... beyond its short-term impact, deep recessions triggered by the pandemic are likely to leave lasting scars through multiple channels, including lower investment; erosion of the human capital of the unemployed; and a retreat from global trade and supply linkages. These effects may lower potential growth and labour productivity in the longer term" (World Bank, 2020a, p. xvl). A computable general equilibrium (CGE) model developed to assess the impact of the pandemic in sub-Saharan Africa based on past experiences of similar crises (notably the 2014 Western Africa Ebola crisis) has found that COVID-19 is likely to have a lasting impact on labour productivity due to its adverse effect on human capital and infrastructure (Djiofack et al., 2020). In the best case, with the disease rapidly contained, the authors estimate the GDP of Africa will be permanently 1 per cent lower than without the pandemic; in the catastrophic scenario, where the crisis lasts more than 18 months, it will be 4 per cent lower for more than a decade. Other studies show that budgets for health have not increased enough to maintain services, especially for the poorer sections of the population across a range of countries (Dash et al., 2020) and there has been a loss of human capital. These effects, however, will vary across regions and the findings for Africa may not apply elsewhere.

Poverty and Hunger

Estimates of people being pulled into poverty vary depending on the poverty line used. They are in the range of 71–100 million for extreme poverty (a poverty line of $1.9 per day) (International Bank for Reconstruction and Development and World Bank, 2020). This implies that global extreme poverty would have increased from 8.2 per cent in 2019 to 8.8 per cent under the baseline scenario (where the decline in GDP is the middle of the projected range) and to 9.2 per cent under the downside (or pessimistic) scenario, where the GDP decline is at the lower end of the range of estimates for 2020. It would be the first increase in global extreme poverty since 1998 and would effectively wipe out progress made since 2017. Even before the pandemic, it was increasingly unlikely that the SDG of reducing extreme poverty to 3 per cent of the global population over the next decade would be achieved (World Bank, 2018). The pandemic puts this goal out of reach. Household incomes are expected to be weighed down by a sharp reduction in employment opportunities, lost earnings due to illness and the fall in remittances (Gupta et al., 2020; Caruso et al., 2021; Chowdhury and Chakraborty, 2021).

At the same time, many people are unable to feed themselves adequately. The World Food Programme (WFP) estimated the number of people suffering from acute hunger throughout the world would double from 135 million at present to 265 million by the end of 2020 (World Food Programme, 2020). Children are particularly vulnerable to a lack of adequate nutrition. An analysis by Lancet found that as many as 6.5 million more children under 5 years of age could suffer from wasting (low weight relative to their height) during the first year of the pandemic, an increase of 14.3 per cent. Without appropriate action being taken, this could result in an additional 10,000 deaths per month (Headey et al., 2020). UNICEF has an online dashboard that collates data from 159 countries to show their performance for different child welfare parameters. It shows that most countries in the low or lower middle income category have experienced drops in nutrition programmes for adolescent girls and boys, as well as in nutrition programmes for schoolchildren (United Nations Children's Fund, 2020). There are also vulnerable groups in developed countries that are facing unprecedented food insecurity, even in the world's wealthiest cities, such as Geneva (Patrick, 2020). A report by Oxfam estimates that there could be more deaths from hunger than from COVID-19 (Oxfam Australia, 2020).

A report by the Food and Agriculture Organization of the United Nations (FAO) highlights that as guardians of household food security, women are also disproportionately affected by the impacts of the pandemic. In most countries, women lead agriculture and related activities, which makes them more vulnerable to the pandemic than men. There is evidence of this phenomenon in previous epidemics, such as Ebola and Middle East Respiratory Syndrome. These diseases have the potential to seriously undermine the empowerment of these women, making gender-disaggregated data, gender-sensitive social security nets and awareness of the gender impact of policy responses vital (Food and Agriculture Organization of the United Nations, 2020c).

Food Prices and Food Security

Average food prices rose modestly in 2020: for 2020 as a whole the FAO food price index was 3.1 percent higher than in 2019.[3] Projections by FAO and other agencies are varied but we are beginning to see the global repercussions of disrupted agricultural production during 2020. The FAO food price monitor showed distressing increases in January and February 2021. This global picture also contains severe local price increases in a number of locations. The International Food Policy Research Institute (IFPRI) has launched a COVID-19 food price monitor that tracks pressure on food prices showed mostly downward trends in 2020, but with some exceptions (Food Security Portal, 2020). For example, last year potato prices in India increased more than 15 per cent and rice prices have also risen in some markets. In Uganda, prices of maize, millet and wheat have gone up more than 15 per cent and some commodity prices have increased in Rwanda and Burundi as well, the two other countries in Africa that are monitored. A long term view of food price movements, however, shows periodic cycles with significant increases followed by declines. The current movements would not stand out in this long run picture.[4]

A number of factors have been identified as the causes of local price rises. Some supply chains are being negatively impacted by a lack of workers and transportation, such as meat processing (Schmidhuber et al., 2020) and dairy (Minten et al., 2020). There are reports that prohibitions on the migration of seasonal farm workers are also impacting crop prices (Gonzalez and Aronczyk, 2020; Schmidhuber and Qiao, 2020). In some places, global supply chains (i.e., the different stages in taking a food item from the grower to the consumer) have broken down and while local supply chains are reorganizing to accommodate this phenomenon, there has been upward pressure on prices in some cases (The Economist, 2020; Food and Agriculture Organization of the United Nations, 2020f). Furthermore, as of April 2020, 17 countries had introduced export restrictions on food items (World Trade Organization, 2020a). While these are a relatively small number compared to previous crises, they nonetheless impact food prices locally, particularly in countries heavily dependent on food imports, such as the small island developing states (Tableau Public, 2020).[5] The same was observed in previous periods when a decline in production of a food commodity is followed by export restrictions, raising prices internationally (Espitia et al., 2020).

In 2020, the problem in most countries was not a food security crisis induced by food prices going up but rather incomes going down (Schmidhuber et al., 2020). The increase in unemployment and poverty referred to above reduces spending on food and raises the level of hunger and undernutrition. At the same time, there are warnings that supply factors could worsen due to falling investment, labour shortages and other aspects of supply chain logistics (Goel et al., 2020). The spread of COVID-19 in slaughterhouses—not from meat itself but from the working and living conditions—is particularly important (Science Media Centre, 2020). More generally, restrictions on movement enacted to prevent the spread of the virus are starting to disrupt the supply of agri-food products to markets and consumers, both within and across borders (Organisation for

[3]FAO Food Price Index | World Food Situation | Food and Agriculture Organization of the United Nations

[4]Food Prices - Our World in Data

[5]According to IFPRI, during the crisis of 2007–08 export restrictions blocked about 11 per cent of the calories that flowed through global markets. In this pandemic similar measures have affected only 3 per cent of supplies but there are signs that the number is going up. See: http://sdg.iisd.org/commentary/guest-articles/covid-19-measures-in-spotlight-at-wto-meeting-on-agriculture/.

TABLE 1 | COVID-19 related impacts on food systems and nature.

	Ecosystems and biodiversity	Pollution	Climate change
Economic impacts	Less funds for enforcement: evidence of increase in poaching, fly tipping, etc. (–) Falling incomes reduce pressure on commercial capture fisheries (+) Unemployment increases pressure on subsistence fisheries and wild food harvesting (–) Less biofuel demand reduces pressure for forest clearance and habitat loss (+) More land clearing to increase provision of food to replace wild meat in some places but more hunting of wildlife in others (+/–)	Less funds to ensure compliance with waste disposal and agrichemical use (–) Lower prices for inputs such as fertilizer, but may lead to overuse (+/–) Less work absenteeism due to lower local pollutants (+)	Less funds to ensure compliance on climate-smart agriculture (–) Less biofuel demand lowering forest clearance- related emissions (+) More land clearance to increase provision of food as a result of higher self-sufficiency (–) Lower emissions due to lower activity (+) Emissions impacts during recovery phase depend on nature of fiscal stimulus (+/–)
Health-related impacts	Diet shifts due to lower incomes (?) Labour shortages reduce crop and livestock productivity, reducing food availability (–) Less human resources to manage land (–) Greater control of use of wildlife in some places (+); less control and more use in others (–)	Diet shifts due to lower incomes (?) Higher mortality rates from COVID-19 in areas where pollution levels are high (–); but lower pollution levels due to lower activity (+) Indoor air pollution worsens as people, primarily women and children, spend more time indoors (–) Restrictions on movement making access to sanitation and safe water difficult (–)	Diet shifts due to lower incomes (?) Lasting shift in production and consumption patterns (?)
Social impacts	Increased pressure on common resources as workers return from urban areas and from overseas (–) Increased pressure on land as workers return from urban areas and from overseas (–)	Possibility of changing use of transport for work and social reasons over the long term with lower local air emissions (+)	Lower GHG emissions under travel restrictions (+); higher emissions due to reduced mass-transit use (–) Possible long-term changes in travel/ transport for all uses, with lower GHG emissions (+)

Economic Co-operation and Development, 2020b; Nandi et al., 2021).[6] How this impacts the wider community will depend on national policy responses. The FAO food price index reported a 4.3 percent global average increase in January, 2021. Rising food prices in 2021 could compound with income loss to create a food security crisis.

IMPACTS OF COVID-19 ON THE NEXUS BETWEEN AGRI-FOOD SYSTEMS AND THE ENVIRONMENT

The economic, health and social impacts of COVID-19 have direct and indirect links to the natural environment and to the way agri-food systems are organized. The UNEP COVID-19 updates list a number of impacts on the environment (https://www.unep.org/covid-19); this section summarizes these impacts and highlights linkages to food systems. The updates also discuss opportunities to mitigate climate change and new risks arising from the pandemic with the potential to accelerate climate change. Similarly, they draw attention to the role of habitat destruction on the propagation of zoonotic diseases such as COVID-19 and the threat facing agriculture sectors, such as rice production, which are being further damaged by the effects of the pandemic.

[6]Real time reports on the impacts of Covid19 and the measures against the pandemic on the everyday life of people are presented on Twitter @CovidFoodFuture or on Medium https://link.medium.com/VkoF73QRRdb

Table 1 provides a list of key ways in which food systems and nature are being affected by COVID-19 and the measures taken to contain it. It groups impacts according to UNEP's three areas for strategic action: ecosystems and biodiversity; pollution; and climate change. The main channels by which these categories are impacted are through the economic, health and social effects of COVID-19. Many environmental impacts—both positive and negative—are related to the economic contraction: on the one hand, less economic activity may reduce pollution and emissions; on the other, shrinking budgets may curtail investment in sustainability and conservation and poverty may increase pressure on natural resources.

Ecosystems and Biodiversity

There has been some evidence that wildlife has benefited from noise reductions and lesser human activity during the lockdowns of 2020 (Chowdhury and Chakraborty, 2021), but the economic downturn is hurting ecosystems where budgets for the management of protected areas are being cut. Due to limited monitoring of these protected areas and limited revenue from tourism the incidence of poaching is increasing in several countries, such as India (Saeed et al., 2020), as well as some countries in Africa (Roth, 2020)[7] and South-East Asia (Briggs, 2020). A UNEP COVID-19 update (United Nations Environment Program, 2020b) details the decline in revenue from great ape tourism in Rwanda, which has been halted due to fears that humans could transmit the virus to the animals. Many protected areas use the income generated from tourism to

[7]Financial Times, 2–3 May, 2020.

fund law enforcement, biomonitoring and staff salaries. Several months without tourism revenue has pushed many protected areas into a financial crisis. The release of staff and the suspension of law enforcement can easily lead to an increase in poaching and encroachment, firstly because there is little law enforcement, and secondly because community members have lost their income and have few other alternatives (Lindsey et al., 2020). Primate sanctuaries and rescue centres are also affected. Despite being closed to tourism, animals must still be fed and operations cannot simply be stopped. All these developments have a negative effect on activities associated with the green economy.

The problems are not confined to protected areas controlled or managed by the state but extend to community-managed areas, where the effects could be even more severe as they often have no state/tax revenue (Lindsey et al., 2020). Populations that depend on these areas are being hit hard, workers are losing their jobs (ibid). Behavioural changes in the very communities that were protecting wildlife and engaged in its conservation may become part of the problem if alternative employment and income opportunities are not found. There have been some signs, such as in Tamil Nadu, India that wild animal hunting has increased to fill gaps in income and the availability of meat (Sathishkumar and Rajan, 2020).

An African Union policy brief (African Union, 2020) reports that lockdowns will increase wildlife poaching. Many wildlife management authorities in Africa are semi-autonomous, largely relying on revenue from the tourism industry. However, an unprecedented decline in the number of international visitors is reducing revenue (Lindsey et al., 2020). Conservation in many places depends upon tourism revenue (Buckley, 2020). Many wildlife trusts will lose significant funding, further pushing communities into protected areas in search of livelihoods. Meanwhile, there are a growing number of calls to ban the trade and consumption of wildlife globally because of evidence that suggests COVID-19 originated in wild bats (Global Wildlife Conservation 2020). However, the links between wildlife, health, gender equality and the environment are complex (Keesing et al., 2010; Ostfeld, 2010; United Nations Environment Programme, 2020a) and bans could have unintended consequences for rural communities (see Section on Environmental Compliance Measures).

The African Union also reports the postponement and in some cases outright cancellation of many sustainable forest management activities (African Union, 2020). Another concern is that forest products will be seen as a means of recovery from the economic downturn created by COVID-19. Governments may resort to licensing extractive industries on public lands to raise the desperately needed financial resources to support socioeconomic development after the pandemic (Buckley, 2020). Deforestation of the Amazon, which soared in 2019 under the Bolsonaro administration, accelerated further in 2020 as South America battled the pandemic. In April, 405 square kilometres of rainforest wilderness was razed, an area almost four times the size of Paris. The Brazil space research agency reports this to be an increase of 64 per cent from April 2019. Deforestation further impacts indigenous people living in those areas, where there is poor access to health care facilities, especially for indigenous women seeking access to sexual and reproductive services, the elderly and for those with underlying illnesses.

Despite all these negative effects, there are also some positives. In Outamba Kilimi National Park, Sierra Leone, the rate of illegal timber harvesting has plummeted to zero, due to the drop in international demand. However, this situation must be carefully monitored, since local enterprises may take advantage of the lull to restock their timber yards with illegal logs in anticipation of the end of the pandemic (Inveen, 2020).

Ecosystems Supporting Agri-Food Systems

In addition to providing habitat for biodiversity, ecosystems support food and energy sectors that contribute to human health, livelihoods, and wellbeing. The provision of these ecosystem services are also being impacted by the pandemic. Examples are biofuel, rice production, and fisheries.

Biofuel Demand

Less demand for all fuels, including biofuels, owing to falling demand for transportation and lower oil prices has reduced demand and prices of feed stocks (Schmidhuber and Qiao, 2020). Biofuels contribute to powering transportation systems, but they also drive conversion of land use to biofuel crops. The fall in travel associated with the pandemic should also reduce biofuel demand and thus the incentive to clear land for growing fuel crops, but so far, there is no evidence that this has changed the pressure on forest clearance. The question of what happens to land that was used for biofuel production merits further investigation.

Rice Production

UN agencies have highlighted the adverse effect of COVID-19 on rice production and exports (United Nations Environment Programme, 2020c; Food and Agriculture Organization of the United Nations, 2020d). Pandemic-induced panic buying has encouraged some rice exporting countries to impose bans on exports, which has affected importing countries. Meanwhile, extended lockdowns in major rice producing countries have delayed the acquisition of inputs like fertilizers and seeds by local farmers (Esiobu, 2020). Restrictions on the movement of farm labourers could affect planting and harvesting, reducing future yields (World Bank, 2021). These supply disruptions will increase prices. Price surges disproportionately harm poorer households, for which rice is a staple and accounts for a significant proportion of monthly spending.

Commercial and Subsistence Fisheries

Fisheries have also suffered mixed impacts from the pandemic. A drop in demand has hurt commercial fisheries but may improve wild fish stocks in the short term (Food and Agriculture Organization of the United Nations, 2020e). Commercial fisheries may also suffer labour shortages and transportation disruption (Marschke et al., 2021). Studies show that in island countries and coastal areas, people who are unemployed may turn to fishing for food and income, increasing pressure on near-shore fish stocks. The pandemic may also exacerbate unregulated and unreported small-scale fishing in some areas, while in other areas the drop in demand may increase poverty in fishing communities (Bennett and Robinson, 2000).

Pollution

COVID-19 has been linked to harmful emissions in air, water and the land. Although these impacts do not directly implicate agriculture or food systems, they have important economic, health and social consequences. They also point to potential measures that can be applied in the agricultural sector and for food systems as part of rebuilding better, as discussed later.

Air Emissions

Emissions of nitrogen dioxide (NO_x) and particulate matter (PM) have declined notably across many countries (Berman, 2020). NO_x satellite measurements of air quality for China, South Korea, Italy, Spain, France, Germany, Iran, and the United States (early epicentres of the virus) all show reductions from 20 to 40 per cent in NO_x at times during the first half of 2020. On particulate matter, a study focused on China reported a 35 per cent reduction in $PM_{2.5}$ (Shi and Brassuur, 2020) while the reduction in India was estimated to be 43 per cent for $PM_{2.5}$ and 16 per cent for NO_x (Sharma et al., 2020).

Reductions in PM concentrations have not been observed throughout the world. The European Environment Agency reports that although NO_x concentrations have declined across the continent, a consistent reduction has not yet been observed across European cities (EEA, 2020). This is likely due to the fact that the main sources of this pollutant are more varied. In Europe, they include the combustion of fuel for heating residential, commercial and institutional buildings, as well as industrial activities. A significant fraction of particulate matter is also formed in the atmosphere from reactions of other air pollutants, including ammonia, which, in Europe is typically emitted by the application of agricultural fertilizers in the spring. Unfortunately, reductions in NO_x have coincided with increases in surface ozone. An analysis of China noted that the decline in $PM_{2.5}$ has been accompanied by an increase in concentrations of secondary pollutant surface ozone in the country of 150–200 per cent (Shi and Brassuur, 2020). Similarly, ozone concentrations in India have increased by 16 per cent (Sharma et al., 2020). This increase is probably a direct consequence of the declines in NO_x on the presence of volatile organic compounds, since photochemical reactions between these two pollutants can result in higher ozone levels when NO_x concentrations decline.

Changes in emissions of these harmful pollutants could significantly reduce premature mortality and morbidity, as well as losses from absenteeism.[8] Links between concentrations of these pollutants and these health and work-related impacts at the global level are well documented (World Bank and Institute for Health Metrics and Evaluation, 2016) but there is not as yet an evaluation of the gains in terms of lives saved or reduced health and absenteeism costs associated with the current reductions.

[8]Given the reductions in output and demand for labor due to the virus, the effect on absenteeism will not be as important as it is under normal conditions.

Air pollution and higher concentrations of these pollutants have been linked to increased hospitalization and death from COVID-19 infection. New research has found that long-term exposure to air pollution may be "one of the most important contributors to fatality caused by the COVID-19 virus" around the world (Ogen, 2020). The study examined COVID-19 fatalities in four European countries that have been hit hard by the virus (Germany, France, Italy and Spain). It found 78 per cent of deaths occurred in just five regions in northern Italy and Spain. These regions had the highest concentrations of nitrogen dioxide (NO_2), a pollutant harmful to human respiratory systems. Moreover, the geography of these regions meant they also suffered from downward air pressure, which can prevent the dispersal of airborne pollutants. The findings of another recent study on the United States are similar: an analysis of 3,080 counties found that even a small increase in long-term exposure to air pollution could have a significant impact on the severity of COVID-19 symptoms (King, 2020). It suggests that lowering the average amount of airborne PM in Manhattan by just 1 μg over the past 20 years could have led to 248 fewer deaths from the disease so far.

In addition to weakening our respiratory systems and making us more susceptible to COVID-19, air pollution might also be functioning as a vector for transmission for the virus. Scientists in Italy have detected coronavirus on particles of air pollution, which could, they believe, help the virus spread (Setti et al., 2020). However, these findings are preliminary.

The third link between COVID-19 and air quality relates to increased exposure to indoor air. The increase in the number of people remaining indoors as a result of the coronavirus pandemic makes managing indoor air pollution even more important. In developing countries, there are also emissions from the combustion of wood and coal inside homes. The Stockholm Environment Institute notes that in many developing countries, COVID-19-related measures requiring people to stay indoors and at home could increase exposure to indoors emissions. For example, exposure to air pollution among members of households who spent more time at home and use coal for cooking in Accra, Ghana, was twice as high as members who spent more time outside (SEI, 2020). Globally, three billion people still cook using unclean fuels and technologies leading to household air pollution further undermining their health. According to the WHO, "3*.8 million people a year die prematurely from illness attributable to the household air pollution caused by the inefficient use of solid fuels and kerosene for cooking*." Exposure is particularly high amongst women and young children who spend the most time near the domestic hearth, further reducing their immunity against zoonotic diseases including COVID-19 (World Health Organization, 2018).

Access to Water

In many communities around the world, a lack of a clean water supply and adequate sanitation deprives people of their most basic protections against the spread of the virus. This means that where handwashing is limited and waterborne diseases are already common COVID-19 could spread more easily (United

Nations Environment Programme, 2020d). This aspect is also related to gender (United Nations Children's Fund, 2016). In many parts of the world, women and girls spend hours every day fetching water or waiting in crowded queues for water vendors, potentially increasing their risk of exposure to the virus. Their health and consequently their wellbeing could be further compromised if they struggle with these tasks because they are ill or have to care for people who are sick.

Climate Change

GHG Emissions

The International Energy Agency (IEA) estimates that global GHG emissions fell by about 8 per cent in 2020 due to contractions in demand for travel, transport and energy (International Energy Agency, 2020a). The UNEP Emissions Gap Report in 2019 estimated that to limit global warming to 1.5°C, emissions would need to continue to fall by 7.6 per cent on average every year for the next 10 years (United Nations Environment Programme, 2019). These figures show the scale of the challenge we face in order to reduce GHG emissions.

There is also some evidence of a rebound effect, whereby this fall in emissions may be reversed in the extremely short term, partly as fear of infection makes people avoid public transport and switch to private vehicles with higher per capita emissions (a trend already partly observed in China). A similar reversal was observed after the 2008 crises. In April, 2020 when most countries were in lockdown, fossil fuel emissions were 17 per cent lower compared to the comparable 2019 figure (Le Quéré et al.,). However, the easing of restrictions has reduced this figure to just 5 per cent below the 2019 average and emissions in China have already rebounded to pre-pandemic levels (Integrated Carbon Observation System, 2021). As such, any fall in emissions due to the pandemic should be seen as temporary.

Deforestation and Land Clearing

FAO has argued that COVID-19 could increase widespread forest loss (Food and Agriculture Organization of the United Nations, 2020c). The CEO of Conservation International notes, "poaching and deforestation in the tropics have increased since COVID-19 restrictions came into force around the world, according to recent reports from Conservation International field offices", stressing that "a surge in agricultural expansion and illegal mining has accelerated forest loss in Brazil and Colombia" (Price, 2020). Preliminary evidence suggests that this is due to the reduced presence of government, policing organizations and NGOs in areas prone to illegal logging (Amador-Jimenez et al., 2020; Fair 2020). The links between the pandemic, enforcement of land-clearing prohibitions and demand for land for food and fuel crops are complex and merit further investigation.

Compound Human Health Impacts

Diet-related health conditions appear to increase the mortality and morbidity of people who become infected with COVID-19. Just as air pollution may worsen infection rates and symptoms, non-communicable diseases (NCDs) like diabetes, heart disease and obesity have been linked to increased rates of infection, hospitalization, intensive care and death (Popkin et al., 2020). Studies from Mexico, China and the United States have identified a connection between NCDs and the severity of COVID-19 infections (Azarpazhooh et al., 2020; Hernandez-Galdamez et al., 2020; Popkin et al., 2020). These compound morbidities are highlighted here because of the relationship between food systems and NCDs (Global Panel on Agriculture and Food Systems for Nutrition, 2016; Branca et al., 2019). It appears that healthier diets and the consequent lower incidence of NCDs could increase global resilience to COVID-19. Researchers have noted that tackling hunger and obesity requires a food systems approach (Steiner et al., 2020). Poor access to nutritious foods and the availability of inexpensive, high-calorie foods are associated with an increasing prevalence of NCDs globally. The connection between obesity and the severity of the pandemic provides further evidence for the urgent need for systemic improvements to food systems but is also an area where further research is required.

COPING STRATEGIES AND THEIR IMPACTS

Strategies are classified in this section under the following headings: monetary and fiscal stimuli; international aid and transfers; targeted support for agriculture; and targeted support for the environment.

Response Through Monetary and Fiscal Stimuli

The fiscal and monetary stimulus provided by governments as part of the global response to the pandemic has been unprecedented. Globally, in late 2020 the level of fiscal stimulus stood at approximately $11.7 trillion as of September 2020, equivalent to nearly 14 per cent of global GDP (International Monetary Fund, 2020a). Fiscal support packages cover a wide range of measures that aim to replace lost household income and business revenues. They include easing or delaying payment obligations for taxes, utilities, rents and servicing debt (International Bank for Reconstruction and Development and World Bank, 2020). As of June 2020, the G20 countries were estimated to be providing $7.6 trillion in fiscal support, equivalent to 11.2 per cent of their combined GDP for 2019. Of this sum, $4.1 trillion has supported direct government spending, $2.6 trillion for credit enhancements and $0.8 trillion for tax relief (Segal and Gerstel, 2020). Several central banks have also loosened their monetary policy in the wake of the pandemic (International Monetary Fund, 2021). In most advanced economies, this has brought already low interest rates close to or below zero (Organisation for Economic Co-operation and Development, 2020a). Countries have also implemented extraordinary measures to ease tight credit markets by purchasing corporate debt. This approach follows in the footsteps of the financial crisis of 2008 and marks the second time major economic problems in the private sector have been tackled by a massive increase in public debt.

Policymakers in emerging market and developing economies (EMDEs) have also used a range of monetary and fiscal measures to respond to the pandemic. In terms of monetary policy, they have supported the flow of credit, with several central banks sharply lowering interest rates and some complementing this with asset purchase programmes similar to those in advanced economies. In terms of fiscal policy, most EMDEs have announced fiscal policy support to confront the immediate health crisis and save lives, limit the scale of the economic contraction and accelerate the eventual recovery. At least three-quarters of EMDEs have increased funding for health care systems to expand testing and hospital capacity. Fiscal support has targeted the expansion of the coverage of social protection, including wage subsidies to protect jobs, cash transfers to households and increased access to unemployment benefits. Measures have also been implemented to ensure continued access to critical public services for vulnerable groups, including low-income households and the elderly (Argentina, Indonesia, Pakistan, the Philippines and Russia). Lastly, several countries have supported strained food systems through subsidies for inputs and cash transfers for food purchases (Organisation for Economic Co-operation and Development, 2020c; ONE n.d.; World Trade Organization, 2020b).

However, in some of the worst affected EMDEs, the fiscal response is constrained by the insufficient tax base and the lack of borrowing potential. In India the pandemic led to a significant contraction in tax revenues, causing the fiscal deficit for 2020–21 to balloon much higher than the budgeted 3.5 per cent.[9] This limits the scope of government support and highlights the need for access to additional resources and to make public spending more efficient. Many developing and low-income countries are likely to face fiscal constraints as a result of high existing debt-to-GDP ratios and the risk of inflationary pressure (Institute of International Finance, 2020). India, for example, has put together a 20 trillion Rupee ($266 billion) relief package, which is among the largest in the world and amounts to roughly 10 per cent of the country's GDP.

Response Through Aid Transfers and Debt Relief

Specific funds for poor countries to address COVID-19 include:

- Lending of up to $150–160 billion from the World Bank, particularly for efforts to support vulnerable populations in client countries.[10]
- The IMF has doubled access to its urgent facilities (Rapid Credit Facilityand Rapid Financing Instrument), allowing it to meet around $100 billion of demand for financing. The IMF has also offered immediate relief for servicing debts to 29 countries under its revamped Catastrophe Containment and Relief Trust, as part of its response to help address the impact of the COVID-19 pandemic.
- The European Union is making €15 billion available to help poor countries (particularly those with weak health care) fight the coronavirus epidemic and assist with the long-term economic recovery.[11]
- The G20 countries have agreed to suspend debt servicing on around $11 billion of official bilateral credit to poorer countries. The IMF, the World Bank and the G20 have also called for private-sector creditors to replicate this measure, which could add a further $7 billion of relief. Individual countries are also ramping up aid programmes for COVID-19.

While the amounts involved are clearly substantial, they must be considered in the context of the size of the crisis and the impact it will have on international aid in general. It is probable that COVID-support will drive overall reductions in global aid.[12] Furthermore, emergency support will also shift the focus away from other development programmes.[13] Global official development assistance levels could drop sharply by around $25 billion by 2021, with the prospect of a protracted economic recession causing donors to reallocate their external budget to domestic spending and revival.[14] This would amount to about 16 per cent of total official development assistance for 2019. In other words, spending in response to the pandemic may not result in additional net resources for developing countries.

Similarly, shift in budgets towards acute health could see a reduction in support for environmental protection and agriculture. There is already some evidence of less funding for the environment as stated in the previous section.

Furthermore, many investments have not been designed to address persistent underlying inequalities. In support of gender mainstreaming efforts in countries responses, the UN Inter-Agency Network on Women and Gender Equality (IANGWE) has published guidelines for *integrating gender equality in the implementation of the UN framework for the socioeconomic response to COVID-19;* and UNDP and UN Women have published a "*COVID-19 Global Gender Response Tracker*", which monitors policy measures enacted by governments worldwide to tackle the COVID-19 crisis, and highlights responses that have integrated a gender lens. The tracker which is still a work-in-progress shows that in July 2020, of the measures taken in response to COVID pandemic, only 42% are gender-sensitive. The tracker, includes 2,500 measures across over 206 countries to examine government measures taken in response to COVID-19 with a gender lens. The measures are

[9]https://theprint.in/economy/pandemic-pushes-indias-fiscal-deficit-to-9-5-in-2020-21-estimated-at-6-8-in-2021-22/595806/ ; https://www.businesstoday.in/current/economy-politics/govt-keeps-expenses-check-amid-covid-19-spending-april-oct/story/423404.html

[10]https://www.worldbank.org/en/news/press-release/2020/04/17/world-bankimf-spring-meetings-2020-development-committee-communique

[11]https://www.euractiv.com/section/development-policy/news/eu-announces-e15-billion-to-fight-virus-in-developing-countries/

[12]https://devinit.org/resources/how-aid-changing-covid-19-pandemic/

[13]https://www.un.org/development/desa/en/news/sustainable/sustainable-development-goals-report-2020.html

[14]https://devinit.org/resources/coronavirus-and-aid-data-what-latest-dac-data-tells-us/

spread across three areas: those that tackle violence against women and girls, support unpaid care, and strengthen women's economic security.

Support for Agriculture and the Environment in Responses to COVID-19

As noted, the bulk of fiscal support has taken the form of cash transfers and additional resources for health services. The IMF Policy Tracker for COVID-19 cites a few examples of fiscal policies specifically targeting the agricultural sector but none focused on the environment.[15] Of those that target the agri-food system in general very few pay attention to the environmental aspects of food production and consumption. The support mentioned for Afghanistan, Bangladesh and Nigeria are partial exceptions.[16] Some other examples of national interventions to support agriculture and the environment are detailed below.

Support for Agricultural Inputs

The FAO recommends four measures to ensure supply of agricultural inputs: reduce farmer income uncertainty; support digitization of input markets; ease movement restrictions for procuring ag inputs; maintain government support for investment in ag inputs (Food and Agriculture Organization of the United Nations, 2020g). Some countries have heeded this advice. In India, the national relief package includes the provision of 300 billion rupees ($4.5 billion) of additional emergency working capital funding for small and marginal farmers to meet post-harvest spring (*Rabi*) and current autumn (*Kharif*) requirements. Several countries, including Angola, Haiti, Kyrgyzstan, Liberia and Senegal, are providing similar financial assistance, supported in part by agencies like the World Bank to address the reduction in access to finance among farmers (World Bank, 2020b).

Support to Develop Local Supply Chains

Transport problems have caused delays to the provision of inputs and migrant labour has become less accessible. These transport problems were caused by lockdowns and COVID-19 related travel restrictions which impacted the free movement of vehicles.[17] In response, communities are developing local supply chains with some support from governments. In India, the Mayurbhanj District Administration launched the "Mayur fresh on wheels" initiative, with small vans delivering vegetables to people's houses with the slogan "Stay at home, eat safe". The initiative cuts out intermediaries by promoting farm-to-door delivery. India has also implemented the Farmers' Produce Trade and Commerce (Promotion and Facilitation) Ordinance 2020, which will promote barrier-free trade and commerce between and inside states of farm produce outside the physical premises of official markets.

In other countries, local initiatives are supporting direct market linkages between sellers and consumers. For example, vegetable supply bases around cities in China are ensuring smooth supplies of produce despite lockdowns (Food and Agriculture Organization of the United Nations, 2020b). In Kenya, the World Bank is providing $1 billion through a development policy financing facility that will support significant reforms and deregulation in the agricultural sector. This includes facilities to allow farmers to buy inputs such as fertilizers and seeds electronically using vouchers on their mobile phones. However, the scheme has been criticized by advocates of local food systems for promoting the seeds and fertilizers of multinational companies at the expense of local supply chains.[18]

Freer Movement of Trade

These measures are in addition to others that seek to ensure global supply chains remain open and function efficiently. Net food importers face dangerous supply risks (Giordano and Ortiz de Mendívil, 2020). A deficit in its domestic maize supply had led Kenya to import maize from Uganda. However, since April, mandatory coronavirus tests for drivers at the border between the two states have seen queues of lorries stretching up to 30 km.[19] After some countries moved to restrict exports of food products,[20] a powerful consortium of WTO member states (including the United States, China and the European Union) issued a joint statement on April 22, 2020 discouraging export restrictions and noting that they could lead to food insecurity. Its signatories committed not to impose export restrictions and to supporting WTO research and dialogue to ensure the function of agri-food supply chains (Food and Agriculture Organization of the United Nations, 2020a).

Cash Support Programmes for Informal Workers

As many as 84 countries have introduced or adapted social protection programmes; this includes 97 targeted cash transfer schemes, though only 10 countries, mainly in Latin America, specifically targeted informal workers. The amounts ranged from $39 in Colombia to $153 in Thailand. They were mostly one-off payments, except in Brazil with a monthly payment for three months (Food and Agriculture Organization of the United Nations, 2020b).

Food Support Programmes

Some countries have also provided specific support in the form of free or subsidized food and some public bodies are proactively

[15]https://www.imf.org/en/Topics/imf-and-covid19/Policy-Responses-to-COVID-19

[16]https://www.imf.org/en/Topics/imf-and-covid19/Policy-Responses-to-COVID-19

[17]https://www.iea.org/articles/changes-in-transport-behaviour-during-the-covid-19-crisis

[18]https://www.oaklandinstitute.org/blog/world-bank-covid-19-assistance-kenya-benefits-multinational-agribusiness-agrochemical

[19]https://www.one.org/africa/about/policy-analysis/covid-19-tracker/country-deep-dives/

[20]https://public.tableau.com/profile/laborde6680#!/vizhome/ExportRestrictionsTracker/FoodExportRestrictionsTracker

providing free meals. For instance, in India several women's self-help groups have mobilized to fill gaps in the provision of masks and sanitizers and in Delhi, free lunch and dinner are served at all local government night shelters (World Bank, 2020a).

Several countries have announced policies to address the disruption to school meals or food supplies to supplement cash transfers. The Government of Colombia has guaranteed the continuity of the provision of food to schoolchildren under its flagship school meals programme. It also plans food packages for 250,000 elderly people who are not receiving the corresponding cash transfer. In countries such as Afghanistan where such programmes are not in place, the government and development partners are using community development programmes, providing assistance to grain banks and supporting the distribution of food, as well as other necessities, to people in need, at the community level.[21] In Pakistan, over 18,000 households (mainly female-headed) will receive support to develop kitchen gardens, small-scale livestock rearing and farming.[22]

South Africa provides an innovative example of "spontaneous venturing", with local supply chains (small informal shops and redeployed tourism staff) used for the humanitarian distribution of food parcels, linking emergency food aid to maintaining rural communities that rely on biodiversity and the benefits it provides as their main source of livelihood.

Environmental Compliance Measures

The environmental policy measures most directly related to COVID-19 target the spread of zoonotic diseases from wild animals.[23] China has outlawed the hunting for food and consumption of terrestrial wild animals, reinstating previous legislation designed to prevent the spread of viruses from animal species.[24] It is not clear how many other countries have introduced restrictions on wild meat but there is considerable pressure to do so by government agencies, civil society and international organizations. The United Nations Convention on Biological Diversity calls on countries to help prevent future pandemics by better controlling all types of wildlife markets. However, their widespread bans can have unintended consequences, affecting low-income rural communities that depend upon wild animal hunting. For example, the Ebola crisis and the subsequent ban on the wide meat trade and markets across West and Central Africa resulted in unemployment for thousands of women, who are the primary traders of wild meat (Bonwitt et al., 2018).[25]

India is one of the countries whose COVID-19 relief package has addressed environmental issues, with 60 billion rupees ($860 million) of funding for employment related to forest management and soil and moisture conservation works. Kenya is another example and the Government has set aside two billion shillings ($18.6 million) for community wildlife conservation affected by the fall in tourism.[26]

Many of the greatest impacts of COVID-19 on the environment and food systems will come from the policy measures taken by countries and international agencies to mitigate the pandemic and recover from the crisis, and whether or not these measures account for all environmental, gender, and socioeconomic impacts. Fiscal constraints have limited—and will increasingly limit—the capacity to implement support measures, especially in low- and middle-income countries. The next section uses these examples and lessons from the sustainable development agenda to look forward to how countries can build back better.

LESSONS FROM COPING WITH COVID-19 AND THE WAY FORWARD

The outbreak of COVID-19 and the fast global spread of the virus created a need for rapid response from governments all over the world. Strengthening health care systems and mitigating the economic impacts of the measures taken to contain the virus were packaged in several budgetary aid measures at both national and international level. Because of the unique situation and the urgency of the measures, states did not follow one grand design but had to readjust spending based on the latest developments and needs. In the following section we draw first lessons from the action taken by governments (as of end of August 2020).

Lessons From the Measures Taken So far

The measures in the previous section raise five important messages. First, while significant resources are being allocated to tackling the crisis, there are still areas where support must be scaled up or strengthened, especially to address undernutrition and food insecurity[27] and associated, gender-related, socio-economic factors. The UN World Food Programme has warned the international community that the world could face a huge food crisis and is lobbying for more investment in food aid.[28] Even in wealthy countries, the rise in the use of food banks[29] can be partly explained by insufficient cash provision from the state. While emergency funding will help address the increase in food insecurity, it is not enough. FAO has publicly

[21]https://www.worldbank.org/en/topic/poverty/brief/poverty-and-distributional-impacts-of-covid-19-potential-channels-of-impact-and-mitigating-policies

[22]https://www.worldbank.org/en/topic/agriculture/brief/food-security-and-covid-19

[23]It is important to recognize that the source of the current pandemic is not yet confirmed. Nonetheless, linkages to animals (including wild and domesticated animals) are being investigated and there are influenza strains that can be transferred from domesticated animals such as pigs. See https://www.sciencemag.org/news/2020/06/swine-flu-strain-human-pandemic-potential-increasingly-found-pigs-china.

[24]https://www.cifor.org/feature/covid-19-and-wild-meat/

[25]https://www.research.ox.ac.uk/Article/2020-04-16-the-covid-19-response-and-wild-meat-a-call-for-local-context

[26]https://www.nation.co.ke/kenya/news/what-is-in-it-for-you-in-uhuru-s-stimulus-package–306398

[27]https://www.africanews.com/2020/05/14/coronavirus-africa-covid-19-could-deepen-food-insecurity-malnutrition-in-africa/

[28]https://www.reuters.com/article/us-wfp-aid-idUSKBN26Y1S4

[29]https://www.nytimes.com/2020/04/08/business/economy/coronavirus-food-banks.html

raised awareness on the COVID-19 related challenges for African food systems.[30]

Second, the support packages being implemented are very much concentrated on short-term relief and the limited fiscal resources of most developing countries mean it is unclear how long they can continue. Given the second wave of the pandemic and persistent infection rates in many of these countries, the outlook could be extremely challenging, since fiscal room for manoeuvre is even more limited. This implies the need for more sustained international support in 2021 and possibly even after the COVID-19 threat has subsided to ensure a sustainable and equitable food system.

Third, there is a real concern that focusing on COVID-19 fiscal measures risks less resources for sustainable development in general and the crowding out of other important programmes that target the SDGs in 2021 and beyond. A report by Development Initiatives has flagged a potential fall in official development assistance of $25 billion in 2021 (Development Initiatives, 2020). It is too early to assess how much the budgetary spending on COVID-19 will impact the achievement of the SDGs. Further research will be needed to monitor how the bail-out packages have contributed to achieving 'fewer people living in extreme poverty, less gender inequality, a healthier natural environment and more resilient societies' (UN Secretary General, March 2020).

Fourth, there has been a panoply of measures to support the agri-food sector, ranging from emergency financial support to farmers to more structural support for local supply chains; and new support measures are being launched based on short-terms needs in different countries. Going forward it will be critical to ensure that the right signals are sent to agents throughout the food sector to ensure its long-term recovery. Emergency relief must be more consistent with long-term objectives for sustainability, resilience, equity and gender equality.

Lastly, the measures have so far mostly ignored linkages to the environment, including the need to prevent further loss and degradation of habitats, which can facilitate the animal-to-human transmission associated with the spread of zoonotic diseases such as COVID-19. This has to be addressed.

The Way Forward

The ongoing investments in programmes initiated to respond to COVID-19 are a clear indicator that the support initiated at the beginning of the pandemic will need country specific follow-up and will need to be strengthened in areas where they have proved inadequate. Key to any program will be the need to monitor the different impacts of the pandemic. Particularly important will be the impacts on the agrifood system and the environment. While country experiences have a lot in common, they also have many differences. These need to be taken into account in designing measures and that in turn will need careful tracking of the evidence.

As the disruptions in production that occurred during 2020 begin to affect food prices, more resources will be required to prevent undernutrition and food insecurity, ensure that local food supply systems function efficiently and protect the ecosystems that underpin the whole agri-food system. At the same time, it is also important to move from crisis intervention in the early phases of the global pandemic to a longer-term strategy of how to build back better. To be sure, the effects of the pandemic will be present for a long time, through lower investment, the erosion of human capital and declines in global trade and supply linkages. Taking these lasting impacts into account, it is critical that the recovery addresses both the economic, social and the environmental challenges that lie ahead. It should be possible, as the title of this article suggests, to build back better, by taking advantage of positive changes in behaviour during the crises to change the way in which we travel, produce and consume food, and use our environmental resources.

Building Back Better means rethinking the paradigm of aid and development assistance. The pandemic has shown that national borders are irrelevant to global issues like health, food security and sustainability. Rather than following traditional approaches to international development, the path forward should be for *global* development that relies upon multi-scaler analyses and identifies problematic dynamics between larger and smaller and richer and poorer countries (Oldekop et al., 2020). The path should also prioritize support for companies and agencies for a resilient and economically-just recovery.

The way forward comprises three parts: measures to be taken immediately, over the next six to nine months; short-term measures, covering the next year; and deeper changes in the medium term that alter human behaviour and the structures that engender production and consumption to meet the SDGs. The proposals set out here complement the United Nations' framework for urgent socio-economic support to countries and societies in the face of COVID-19 (United Nations, 2020) and further develop the UNEP 10 Principles for Recovery.[31]

Immediate Measures

In line with the evolution of the pandemic in 2021 and beyond, the current measures will need to be maintained and even strengthened in areas where they are weak. Loss of income of people having been negatively affected by lockdowns remains a problem that prevents adequate access to food, people living in poverty struggle to isolate (Brown et al., 2020); health services are under pressure and resources to protect the environment are declining. These issues must be addressed urgently. The problems are greater in more unequal societies. COVID-19 is also showcasing that already existing inequalities have been increased by the pandemic. As the development economist Jeffery Sachs notes, "high inequality undermines social cohesion, erodes public trust, and deepens political polarization, all of which negatively affect governments' ability

[30]https://timesofindia.indiatimes.com/world/rest-of-world/fao-calls-for-immediate-investment-to-sustain-africas-agriculture-post-covid-19/articleshow/76179325.cms

[31]https://www.greengrowthknowledge.org/sites/default/files/downloads/resource/SustainableInfrastructure-PrinciplesforRecovery.pdf

and readiness to respond to crises".[32] (Sachs, 2020). The crisis is not hitting all people in the same way despite the fact that all humans are susceptible to the virus.

In the agri-food sector, the most pressing issues are ensuring the supply of inputs (including labour) and addressing difficulties in the transportation of food inside countries. The challenges of access to food, transportation of food to markets and maintaining food supply on informal markets are described by affected people in real time[33,34] Even in Africa, a continent with a relatively high level of self-sufficiency, only a fifth of food is eaten by the families that grow it. The rest moves down long supply chains, via lorries, processors and wholesale markets. Those who have land can depend on it for their own needs, but rural households living in poverty buy almost half of their food and a lack of stock in markets is also affecting supply.[35] There have been major supply chain disruptions in many developing countries, especially in sub-Saharan Africa. Action is needed to improve networks for the transportation of food[36] that minimize loss and waste, with simultaneous action needed to develop local (urban and peri-urban) food production.

Given the restrictions on movement, a shortage of labour to work the land can be expected to cripple food systems if not addressed. In general, low-income countries employ higher shares of labour for primary production, leaving them more exposed to direct disruptions in the labour supply, including the labour available to individual farmers. The same holds for labour-intensive production: there are various examples of how production of fruit and vegetables and meat and dairy products have already been adversely affected by labour shortages caused by the pandemic (Schmidhuber et al., 2020). Action is needed to facilitate the movement of workers in the agri-food sector so that demands for their services can be better satisfied while taking measures to prevent the spread of COVID-19 among farm workers by improving working conditions.

Transmission in food processing workplaces has been causing problems. Some of the world's worst outbreaks of COVID-19 have been at meat processing plants owned by multinational corporations in Brazil, Canada, Germany, Spain and the United States. Over 10,000 plant workers have fallen ill in the United States and some have even died.[37] Seafood processing plants are also hotspots, for example in Ghana, where an outbreak at a tuna canning plant owned by Thai Union was responsible for a tenth of the country's COVID-19 cases in May 2020.[38] Action is needed to improve health and safety conditions in workplaces with a high risk of infection.

Actions in the Short Term

In parallel to immediate measures, governments are planning recovery packages for 2021 and beyond. Fiscal recovery from previous crises has tended to be carbon-intensive and pay little heed to environmental concerns.[39] For example, the financial crisis caused CO_2 emissions to fall by 1.44 per cent in 2009; however, the following year, they increased by 5.13 per cent, much higher than the pre-crisis rate.[40] The International Energy Agency is monitoring the COVID-related decline in global CO_2 emissions and states that the year 2020 saw a total drop of around 6%. This was the largest annual decline since World War II, around two billion tons of greenhouse gases have been kept out of the sky. However, in December after the economy grew again, emissions were on the rise again and rose to a level higher than in December2019[41] (International Energy Agency 2020b).

To restart the economy, governments usually turn to sectors where investment can easily be made, often in carbon-intensive sectors, such as construction and airlines. A recent analysis of 17 major economies finds that 30 per cent of total announced stimulus will flow to sectors with an adverse impact on climate change, biodiversity or pollution.[42] To avoid this, specific attention must be paid to different dimensions of the recovery that decouple economic activity from carbon emissions and biodiversity loss. There is a risk that recession could reduce investment in sustainability and that increases in poverty could induce behavioural change to cheap, short-term benefits, which must be avoided. Future research will have to analyse carefully if and how incentives to support recovery have led to a decoupling of growth and emissions. Best examples of recovery without increasing again the emission of CO_2 should be used to describe a pathway to building back better.

The OECD notes that, at the very least, measures taken for recovery should conform to a "do no harm" criterion with respect to the environment (Agrawala et al., 2020). However, we should expect more from governments and measures should actively advance the SDGs. Environmental economists have identified three key no-cost policies that would support progress towards several of the SDGs and provide incentives for long-term sustainable development: fossil fuel subsidy swaps, irrigation subsidy swaps and a carbon tax to benefit the tropics (Barbier, 2020).[43]

[32]https://www.project-syndicate.org/commentary/inequality-fuels-covid19-mortality-by-jeffrey-d-sachs-2020-06

[33]https://medium.com/enabling-sustainability/video-diaries-from-nairobi-phase-ii-navigating-food-insecurity-in-times-of-the-covid-19-pandemic-1efd016b965b

[34]@CovidFoodFuture

[35]https://www.economist.com/middle-east-and-africa/2020/04/23/the-race-to-feed-africa-during-a-pandemic

[36]https://openknowledge.worldbank.org/handle/10986/34080

[37]https://www.businessinsider.in/international/news/almost-12000-meatpacking-and-food-plant-workers-have-reportedly-contracted-covid-19-at-least-48-have-died-/articleshow/75633860.cms

[38]https://www.undercurrentnews.com/2020/05/12/thai-union-ghana-cannery-linked-to-over-500-covid-19-cases-in-country/

[39]Peters, G., Marland, G., Le Quéré, C. *et al.* Rapid growth in CO_2 emissions after the 2008–2009 global financial crisis. *Nature Clim Change* **2,** 2–4 (2012). https://doi.org/10.1038/nclimate1332

[40]http://www.globalcarbonatlas.org/en/CO2-emissions

[41]https://www.iea.org/articles/global-energy-review-co2-emissions-in-2020

[42]https://www.vivideconomics.com/wp-content/uploads/2020/06/200605-Green-Stimulus-Index-1.pdf

[43]A fossil fuel subsidy swap would fund clean energy investments and the promotion of renewable energy in rural areas instead of supporting coal, oil and natural gas. Irrigation subsidies could be redesigned to improve water supplies, sanitation and wastewater infrastructure. Finally, a levy could be placed on fossil fuels to fund natural climate solutions in tropical countries.

Natural capital investment for ecosystem resilience and regeneration (including the restoration of carbon-rich habitats and climate-friendly agriculture) have also been identified as having a long-run multiplier and a strongly positive impact on climate (Hepburn et al., 2020). Other promising avenues include clean energy infrastructure, clean connectivity infrastructure (e.g., low-carbon mobility), general research and development spending, clean energy research and development spending, and spending on education.

Environmental clean-up, investment in sustainable agriculture, safeguarding natural resources and improving energy efficiency generally have positive stimulus effects in the short run, as well as positive environmental effects in the longer run. Programmes that support these dual objectives in the energy sector include energy efficiency measures in buildings (weather-proofing) and in agriculture, which could yield significant cost savings and also be relatively labour intensive. Similarly, upgrading power transmissions systems could reduce the loss of energy. Other programmes include those that target congestion reduction, sustainable and resilient food systems and energy-saving changes in cities. A recent UNEP policy brief outlines many of these "green-economy" options (United Nations Environment Program 2020e).[44] Disappointingly, however, green measures account for less than 0.2 per cent of the total stimulus spending to counter the effects of COVID-19 by the world's 50 largest economies so far,[45] despite evidence from the International Energy Agency that a focus on green-economy recovery options could save nine million jobs per year for the next 3 years.[46]

Regarding agriculture, there is an urgent need to rapidly rethink how we produce, process, market, handle and consume our food, as well as how we dispose of waste. This is the essence of a *food systems approach* to building back better—evaluating all links along the value chain following the concept of a eco-agri-food system.[47] These issues are discussed further in the next section on mid-term measures. In the short term, countries must ensure that relief and stimulus packages reach the most vulnerable, including meeting the liquidity needs of small-scale food producers and rural businesses.[48]

Special attention must be paid to water management. A critical priority area will be preparing for potentially significant unplanned irrigation withdrawals—often used to increase short-run agricultural productivity—ensuring they do not withdraw too much water from aquifers, lakes and rivers.[49] Building back better means constructing more resilient water, sanitation and hygiene systems that will deliver these fundamental services, taking into account the hydrological uncertainties under climate change and growing water scarcity and pollution. In developing countries, there is significant potential to improve the efficiency of certain water infrastructure, in terms of reducing illicit extraction and incentivizing water-efficient agricultural practices. Such improvements can be made by simply upgrading existing infrastructure, which is typically labour intensive. Moreover, this can be done at relatively short notice.

The potential of green investments is huge. The International Resources Panel notes that a 60–80 per cent improvement in energy and water efficiency in sectors such as construction, agriculture, food, industry and transport could deliver cost savings of $2.9–3.7 trillion per year by 2030, generating investment of $900 billion and 9–25 million jobs.[50] Nonetheless, access to financing for such investment, especially where it also addresses other environmental and social goals, remains a challenge.

Another important aspect of the response to COVID-19 is reducing the potential for future pandemics. Animal-to-human transmission is the source of 75 per cent of infectious diseases and livestock rearing and wildlife trade are both significant drivers of global biodiversity loss (Taylor et al., 2001). The harvesting, transport and trade of wild meat and the intensive rearing of livestock have both been linked to the emergence and spread of zoonotic diseases.[51] The likelihood of zoonotic diseases like COVID-19 and Ebola increases with habitat destruction, human encroachment on wildlife and current patterns of unregulated and illegal wild meat trade and consumption and wildlife trafficking.[52] Biodiversity experts warn of even more deadly outbreaks in the future unless habitat destruction is halted.

Following the COVID-19 outbreak, there are growing calls to ban the trade and consumption of wildlife globally. However, the links between the consumption of wild meat, health and the environment are complex. Wild meat is an important financial backstop in parts of Africa, Asia, Latin America and the Arctic, in particular when harvests are poor or when agricultural commodity prices fluctuate, and particularly for women. If alternative sources of food and income are not provided for those who need it, bans on the trade and consumption of wild meat could result in malnutrition among the young and most vulnerable or push the trade underground, thus aggravating contributing factors to the spread of disease (May et al., in press).[53] Such bans could also undermine a valuable incentive for communities to continue to protect wildlife.

Actions in the Medium Term

While recognizing the immense challenges the world faces, the discourse on the post-COVID future is mostly positive about the

[44]https://greenfiscalpolicy.org/policy_briefs/unep-policy-brief-on-building-back-better-role-of-green-fiscal-policies/

[45]https://www.bloomberg.com/features/2020-green-stimulus-clean-energy-future/

[46]https://www.iea.org/reports/sustainable-recovery

[47]http://teebweb.org/wp-content/uploads/2018/10/Layout_synthesis_sept.pdf

[48]https://www.un.org/sites/un2.un.org/files/sg_policy_brief_on_covid_impact_on_food_security.pdf

[49]FAO. 2020. The State of Food and Agriculture 2020. Overcoming water challenges in agriculture. Rome.

[50]https://www.resourcepanel.org/sites/default/files/documents/document/media/building_resilient_societies_after_the_covid-19_pandemic_-_key_messages_from_the_irp_-_12_may_2020.pdf

[51]https://wedocs.unep.org/handle/20.500.11822/32285

[52]https://www.unenvironment.org/resources/report/preventing-future-zoonotic-disease-outbreaks-protecting-environment-animals-and

[53]https://www.scidev.net/asia-pacific/opinions/covid-19-wild-meat-ban-deprives-forest-dwellers/

prospects of building back better. The basis for this optimism is the changes in behaviour observed during the crises. There has been rapid adaptation to remote working and improvements in technology, which has the potential to reduce energy use and GHG emissions (Hook et al., 2020). As economies reopen, we may see a partial return to the pre-crisis normal but some behaviour will also change permanently.[54] One speculative estimate is that up to one-third of the global workforce will continue to work remotely, at least on a part-time basis.[55] The other reason to be optimistic is the strong public support for a positive change in direction, including in the corporate sector (The Economist, 2021).

It is essential to build on these positive forces for a better future. The extent to which behavioural adaptations become embedded after the pandemic will depend on policy choices during the recovery period and the extent and severity of lockdown measures. Moreover, in a rapidly changing external environment, the resilience of institutions and the economy to future shocks must be at the centre of the transition in order to increase the ability to function effectively under a range of shocks and stressful situations, especially in food systems.

Driving Changes in Food Systems

The task for agriculture and food systems in the years to come is huge: providing food security for a population projected to reach 10 billion in 2050. The need to transform food systems was clear before the pandemic struck.[56] This article has shown the additional challenges COVID-19 has created for food systems and how they have influenced the pandemic—from its suspected zoonotic origins to the compound health complications of obesity and NCDs.

Feeding a growing human population in ways that minimize harm to biodiversity is imperative to prevent the emergence of another zoonotic disease like COVID-19 (Batini et al., 2020). While wild meat hunting and trade can threaten endangered species, a shift from wild meat to livestock also raises concerns for many conservationists about deforestation (Bennett and Robinson, 2000; United Nations Environment Programme and International Livestock Research Institute, 2020). Researchers estimate that replacing wild meat in the Congo Basin with livestock such as cattle would mean converting 25 million hectares of forest into pastureland.[57] Additionally, it has to be considered that other sources of protein—such as pigs and chickens—are also highly implicated in zoonoses (Backhans and Fellström, 2012).

The question is what stimulus packages can help to implement better systems in this area? Building back better includes ensuring healthy diets, slashing food loss and waste, reducing GHG emissions to limit climate change and adapting to its inevitable impacts, reversing habitat loss, limiting animal–human disease transmission, developing rural areas to create jobs and to improve the livelihoods of people living in poverty, and maintaining ecosystem services, such as clean water and air, on a rapidly urbanizing planet. Factors such as unequal access to land tenure, financial resources and decision-making power can create economic stress in households, leaving women disproportionately exposed to climate-related food security risks (Nellemann et al., 2011). Securing land rights for local communities can help address these issues to some extent. Health, Education and Gender Equality are key developmental outcomes as well. By addressing these issues simultaneously, we are helping to prevent the future spread of zoonotic diseases and to build resilient, sustainable and healthy food systems. The complexity of these interrelated challenges is systematically analysed, e.g. by the OECD, arguing for a policy response for "building back better".[58]

Tackling these challenges requires a systematic approach, as suggested by The Economics of Ecosystems and Biodiversity for Agriculture and Food (TEEB AgriFood) (The Economics of Ecosystems and Biodiversity (TEEB), 2018). Increasing food production without significant progress on reducing the environmental impacts of food systems is not sustainable in the long run. Estimates of the negative externalities of the food system amount to $12 trillion a year, equivalent to about 8 per cent of global GDP in 2019.[59] While we have yet to realize a comprehensive vision of the whole agri-food system, encompassing social equity and jobs, as well as health and environmental impacts, the steps needed to do so are becoming increasingly clear and momentum in this direction is growing. First steps of implementation of the TEEB AgriFood framework in the standard accounting system of food companies by trying to capture the positive and negative externalities of the eco-agri-food system reveals the potential of True Cost Accounting (TCA) as a tool to monitor and steer the transformation towards sustainability.[60]

The pandemic has also turned our attention to food supply chains. On the one hand, there is a concern that COVID-19 will reduce confidence in global food supply chains, which feed billions and have proven efficient and cost-effective. On the other, there is a growing interest in local supply chains and more environmentally friendly local foods. In practice, being closer does not always mean being greener: it also depends on how produce is grown and the inputs, including fossil-fuel based energy. We need a full life-cycle analysis along the lines proposed by the TEEB report to determine the most effective combination of local and global supply chains, recognizing that there is scope for both.[61] Global supply chains should be used where favoured by comparative advantages, climate and economies of scale, while

[54]https://www.bbc.com/news/business-54413214
[55]https://globalworkplaceanalytics.com/work-at-home-after-covid-19-our-forecast
[56]http://teebweb.org/wp-content/uploads/2018/10/Layout_synthesis_sept.pdf
[57]https://www.research.ox.ac.uk/Article/2020-04-16-the-covid-19-response-and-wild-meat-a-call-for-local-context
[58]https://oecd.org/coronavirus/policy-responses/building-back-better-a-sustainable-resilient-recovery-after-covid-19-52b869f5/
[59]https://www.foodandlandusecoalition.org/wp-content/uploads/2019/09/FOLU-GrowingBetter-GlobalReport.pdf
[60]http://teebweb.org/our-work/agrifood/reports/measuring-what-matters-synthesis/
[61]http://teebweb.org/agrifood/

local ones should be promoted where they can meet the demand more effectively and sustainably.[62] In other words, support should be provided for a shift from tightly controlled value chains to more flexible business models that are resilient to the kinds of shocks food systems will face in the future.[63] (The World Bank programme of e-vouchers for subsidies in Kenya cited earlier in this report is a good example.) Finally, given the inherent uncertainty around how food systems evolve, it is critical for developments in this area to be closely monitored in order to respond correctly.

Protecting Habitats and Preventing the Degradation of Ecosystems

The community of researchers and practitioners has long been aware of the loss of ecosystem services due to the degradation and loss of habitats and biodiversity. The current crisis has made the wider public more aware of these issues. The risk from zoonotic diseases is exacerbated by the destruction of habitats for wild animals and the overexploitation of these species. Arecently released scientific assessment from UNEP and the International Livestock Research Institute (ILRI) argued that unless countries take dramatic steps to curb zoonotic contagion, global outbreaks like COVID-19 will become increasingly common.[64] We must acknowledge the interdependence of nature, humans and food systems, and evaluate the implications of wild and domestic animal consumption for food security, food sovereignty, sustainability and the risk of zoonotic diseases (May et al., in press). In this context, smart regulations and incentives for trade in and consumption of wild meat, combined with adequate measures to ensure compliance, would help achieve the second objective of the Convention on Biological Diversity: *sustainable use of biodiversity*.[65]

One proposal emerging from the crisis with an international implementation plan is called One Health-. It is an integrated approach that prevents and mitigates the threats at animal–human–plant–environment interfaces.[66] This could represent a major contribution to bringing together a number of key players. The issues addressed by the One Health include ways to reduce the zoonotic risks posed by livestock and wild animals as well as reducing the consumption of meat, where appropriate, alongside changes to habitats and land use from agricultural conversion, while improving environmental surveillance. To work the approach must be designed and implemented in a broader systems context. Implementation should also include inviting stakeholders from public health, gender, biodiversity, climate and agrifood systems to develop common guidelines for national stimulus packages (Laurans et al., 2020). This would also capitalize on United Nations inter-agency working groups on biodiversity and health, as well as the One Health tripartite alliance.

SDG targets 15.1, 15.2 and 15.3 set clear objectives for reversing the loss and degradation of animal habitats.[67] This shows the presence of an agenda for measures to reduce the risks of future pandemics. However, the problem is catalysing the action needed to achieve this. Given the enormous costs of the COVID-19 crisis, countries should invest in achieving these goals and in reducing the risk of future pandemics. Surveillance tools must be sharpened and mechanisms applied to regulate threats such as the illegal, unsustainable and unregulated trade in timber and wildlife and the use of toxic pesticides. This will require strong support for the post-2020 Global Biodiversity Framework. One of the lessons learned from COVID-19 pandemic is that more resources allocated to achieve these targets are needed and that governments must prioritize appropriate action.

Promoting Low-Carbon Lifestyles

We have noted the potential for a faster transition to a low-carbon economy and society, and the impetus derived from the pandemic. A key difficulty in implementing the transition to a resilient low-carbon society has been the issue of economic justice and social inequality, since people involved in carbon-intensive sectors could lose out from the transition, with a lack of immediate options for alternative livelihoods. The pandemic is also increasing economic and health inequality both within countries and between rich and poor countries.[68] The impact on employment is more pronounced among people with lower incomes and lower education. Similarly, while debt has increased for low-income households, wealthier households are seeing an increase in savings.[69]

The implications of these factors on policies implemented in pursuit of a low-carbon economy mean that policymakers must be mindful of their distributional effects. One example is promoting remote working to reduce transport-related emissions. Research has shown that the share of work that can be done from home varies significantly for countries with different incomes: in urban areas, this share is only about 20 per cent in low-income countries compared with 40 per cent in high-income countries. Educational attainment, formal employment status and household wealth are positively associated with the possibility of working from home, reflecting the vulnerability of certain groups of workers (Gottlieb et al., 2020). This means that measures to encourage

[62]https://www.ft.com/content/d7a12d18-8313-11ea-b6e9-a94cffd1d9bf

[63]https://oecd.org/coronavirus/policy-responses/building-back-better-a-sustainable-resilient-recovery-after-covid-19-52b869f5/

[64]https://www.unenvironment.org/news-and-stories/story/daily-covid-19-cases-reach-new-high-new-report-examines-how-prevent-future

[65]https://www.cifor.org/knowledge/publication/5397/

[66]http://www.fao.org/asiapacific/perspectives/one-health/en/

[67]Target 15.1: By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements. Target 15.2: By 2020, promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally. Target 15.3: Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species.

[68]https://www.ifs.org.uk/publications/14879

[69]https://www.imf.org/external/pubs/ft/fandd/2020/09/COVID19-and-global-inequality-joseph-stiglitz.htm

working from home will need to be complemented with others to improve access to the infrastructure that makes this possible. A second policy that could reduce GHG emissions is buying locally, avoiding long-distance transport. While such a policy has the potential to reduce transport emissions, it could prove devastating for developing countries that export fresh produce, such as fruit, flowers and livestock products. Moreover, when all life-cycle emissions are taken into account, it may not actually reduce emissions. As such, food system investments should follow the results of life cycle assessments and economic impact analyses. Third, in light of the significant labour supply shock caused by the pandemic, it is important to note that green industries will not be able to hire unemployed workers unless there is a strong programme for retraining and relocation.

The measures described here add up to a substantial program of action, also with a large budget. Although the costs of these measures have not been worked out in detail, one comparison of the figures suggests that the cost of preventing further pandemics over the next decade by protecting wildlife and forests would be just 2 per cent of the estimated financial damage caused by COVID-19, proof that prevention is better than cure (Dobson et al., 2020).

CONCLUSION

The global sustainable development agenda has at its core promoting the resilience and sustainability of food systems via a framework of policies and measures. Strategies to achieve the 2030 agenda have to be designed so as to: i) account for environmental thresholds and trade-offs; ii) promote food security and healthy diets; iii) enhance and protect rural livelihoods; and iv) address the inequalities and injustices that have emerged during the crises and that will continue to prevail during the post-pandemic transition. To be sure, this is challenging, as thresholds are difficult to establish and compromises on trade-offs are hard to reach, but it can be made easier through better evidence.

Support will most certainly be needed from the International community, including the United Nations agencies to ensure effective implementation of this framework. One way of doing this will be to provide support to countries to monitor the environmental impacts of COVID-19. The effectiveness of recovery and stimulus packages should be measured against indicators for progress on the SDGs. Additionally, a United Nations agency could also take the lead in expanding the environmental dimensions of the One Health approach to improve the understanding of linkages and impacts when it comes to zoonotic diseases.

AUTHOR CONTRIBUTIONS

AM was the coordinating Lead Author for the paper. He reviewed the literature, contributed to writing it and responded to internal comments. JS contributed to the writing of the paper, review of the literature and response to internal comments. SH coordinated the project from which this study has been extracted. He also contributed to editing the paper. AM was the project director. He provided a lot of the materials and reviewed drafts of the paper. ST contributed materials for the paper, especially from India and reviewed drafts.

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Understanding Regime Shifts in Social-Ecological Systems Using Data on Direct Ecosystem Service Use

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This paper takes a new look on transition processes in social-ecological systems, identified based on household use of direct ecosystem services in a case study in KwaZulu-Natal, South Africa. We build on the assumption that high dependence on local ecosystems for basic needs satisfaction corresponds to a "green loop" type of system, with direct feedbacks between environmental degradation and human well-being. Increasing use of distant ecosystems marks a regime shift and with that, the transition to "red loops" in which feedbacks between environmental degradation and human well-being are only indirect. These systems are characterized by a fundamentally different set of sustainability problems as well as distinct human-nature connections. The analysis of a case study in KwaZulu-Natal, South Africa, shows that social-ecological systems identified as green loops in 1993, the average share of households using a characteristic bundle of direct ecosystem services drops consistently (animal production, crop production, natural building materials, freshwater, wood). Conversely, in systems identified as red loops, mixed tendencies occur which underpins non-linearities in changing human-nature relationships. We propose to apply the green to red loop transition model to other geographical contexts with regards to studying the use of local ecosystem services as integral part of transformative change in the Anthropocene.

Keywords: regime shifts, social-ecological systems, ecosystem services, human-nature relationships, land use change (LUC), doughnut economy, provisioning systems

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INTRODUCTION

In sustainability research the concept of regime shifts has repeatedly been referred to as a fundamental re-organization of a system, typically resulting in irreversible biophysical change (Scheffer et al., 2001; Biggs et al., 2012; Lade et al., 2013). The rise of global capitalism as the dominant system of production has led to an increase of the frequency and scale of shifting regimes (Millennium Ecosystem Assessment 2005; McMichael 2009; Moore 2015). Several modeling approaches are used to demonstrate the ecological and economic impacts regime shifts create (e.g., Folke et al., 2004; Lade et al., 2013; Levin et al., 2013; SRC 2019). Further transgressing planetary boundaries puts the Earth system at risk of being pushed into an entirely new state (e.g., Steffen et al., 2015). In the Anthropocene, referred to as a beginning new geological epoch in which human activity became the driving force of change, this could mark a regime shift at unprecedented scale (e.g., Steffen et al., 2018).

However, the focus on changing biophysical and economic properties in shifting regimes largely leaves aside *relational* shifts between humans and the ecosystems they co-inhabit. This concerns manifold types of relations, including metabolic, cultural or spiritual relationships of humans and surrounding ecosystems and questions in how far regime shifts alter such relationships. Despite an increasing recognition of the interconnectedness between natural and human system components, to date, examining this interface between human and non-human nature in social-ecological system (SES) research is under-researched. This is likely due to a persistent dichotomic understanding of human-nature relationships in modern science (Moore 2015; Weber 2016). Moving beyond conceptions of nature as a mechanical-causal object, both ontologically and epistemologically, will require a similar paradigmatic shift than the supersession of Newtonian physics by quantum physics at the beginning of the 20th century (*ibid.*). This being an aspiration beyond the purpose and possibility of this paper, we aim to establish an entry point to examine "fundamental shifts in perspectives, world views and institutions" (Folke et al., 2011, 719) required to reconnect humans to the biosphere and transform toward more stable and just regimes in SES.

To explore this dimension of regime shifts, we use household level data on the use of direct ecosystem provisioning services (ES)[1] required to satisfy basic needs to understand such relational shifts in the interaction between human and non-human counterparts in SES. In doing so, we extend a methodological approach developed by Hamann et al. (2015) identifying SES based a characteristic bundle of ES, including energy, food, water and shelter. These authors use cross-sectional data. The novelty of the research is underpinned by the use of panel data which permits to analyze the dimension of time in shifting regimes. This is examined in the case study area in KwaZulu-Natal, South Africa, over the period 1993 and 2011.

Conceptually, the approach is rooted in the "green-to-red loop" transition model that was developed by Cumming et al. (2014) and aims to understand implications of agricultural transitions and urbanization for ES. In this model, two archetypal systems exist. On the one hand, "green loops", or rural-agricultural systems, which are characterized as types of SES in which households tend to heavily rely on locally sourced (direct) ES to satisfy basic needs, e.g., subsistence farming of crops and animals, self-collection of wood for energy, use of locally available building materials for shelter or the fetching of water. In these systems there are direct feedback mechanisms between environmental integrity and human well-being. The authors further describe a "green trap" as the consequence of ecological breakdown caused by overexploitation and degradation of the local natural resource base and reinforced by rural poverty (*ibid.*).

Contrarily to that, "red loops" or urban-industrialized systems denote a type of SES in which households largely rely on faraway (indirect) ES to satisfy the same basic needs. This tends to occur through marketized, transported and packaged ES in a monetary economy. Thus, the economy is built on remote extraction of ES from distant ecosystems which involves a much larger complexity, scale and degree of the division of labor. A "red trap" is described as the consequence of excessive consumption and failure to regulate ecological decline as an economy's resource needs are scaled up. In these systems, the connections to ecosystems are "less obvious and immediate" than in green loops (*ibid.*, p.55). To avoid environmental collapse, both types of systems need to fundamentally re-organize and address distinct sustainability challenges and avoid green or red traps, respectively (**Figure 1**).

The transition from green to red loops involves a variety of historically specific and interrelated factors (Folke et al., 2004; Cumming et al., 2014). This typically leads to *gradually* shifting regimes. However, regime shifts can also occur *abruptly*, for instance when slowly changing variables concur with an external shock that can "tip" the entire system into an alternative state (Biggs et al., 2012). One example of the latter are coral reefs or grasslands have been found highly sensible to invading species (e.g., Levin et al., 2013). Here, the more narrowly a system is defined, the higher the likelihood to find variables that abruptly change in response to shocks or stressors. In systems at higher forms of aggregation it becomes increasingly complex to identify critical thresholds that mark a regime shift. We focus our analysis on the household use of ecosystem services which serve as provisioning systems - and depending on the type of use - may indicate the occurence of a regime shift.

The paper proceeds as follows. The section *Methods and data* presents the case study area as well as the methods and data used to identify regime shifts from changing ES use. The section *Results* presents the changing ES use in the case study area of KwaZulu-Natal in the observation period between 1993 and 2011. Moreover, the spatial distribution is mapped using official shapefile data from the year 2011. The subsequent section discusses the findings focusing on empirical challenges related to the study of regime shifts within archetypal analysis (e.g., Eisenack et al., 2019). The last section provides an outlook on using the presented approach to studying variegated human-nature relationships in the context of transformative change.

METHODS AND DATA

Case Study Area and Data

KwaZulu-Natal is one of nine provinces in the south-east of South Africa (**Figure 2A**). It covers with 9.335.137 hectares some eight percent of South Africa's total land area and with over 10 million inhabitants more than 20 percent of the total population (Stats SA 2012a; Driver et al., 2015). Important economic activities are extractive industries like coal and iron, tourism and trade logistics that revolve around the economic hub Durban which is not only the third largest city of South Africa but also hosts the largest maritime port in Southern Africa. The population in the most

[1]Note that in the remainder of the study we use the abbreviation "ES use" or "direct ES use" interchangeably. For a full classification of ES and a distinction between direct and indirect uses see Millennium Ecosystem Assessment (2005).

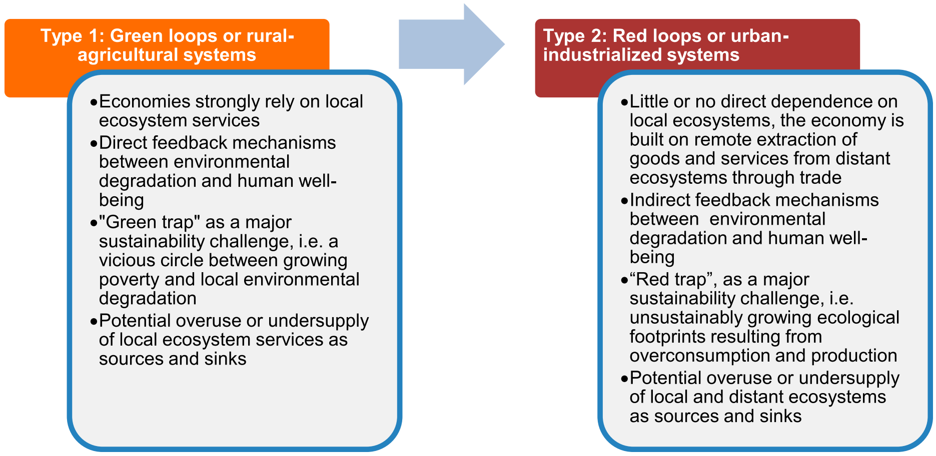

FIGURE 1 | Characteristics of green and red loops and related sustainability challenges. Based on Cumming et al. (2014) and Hamann et al. (2015).

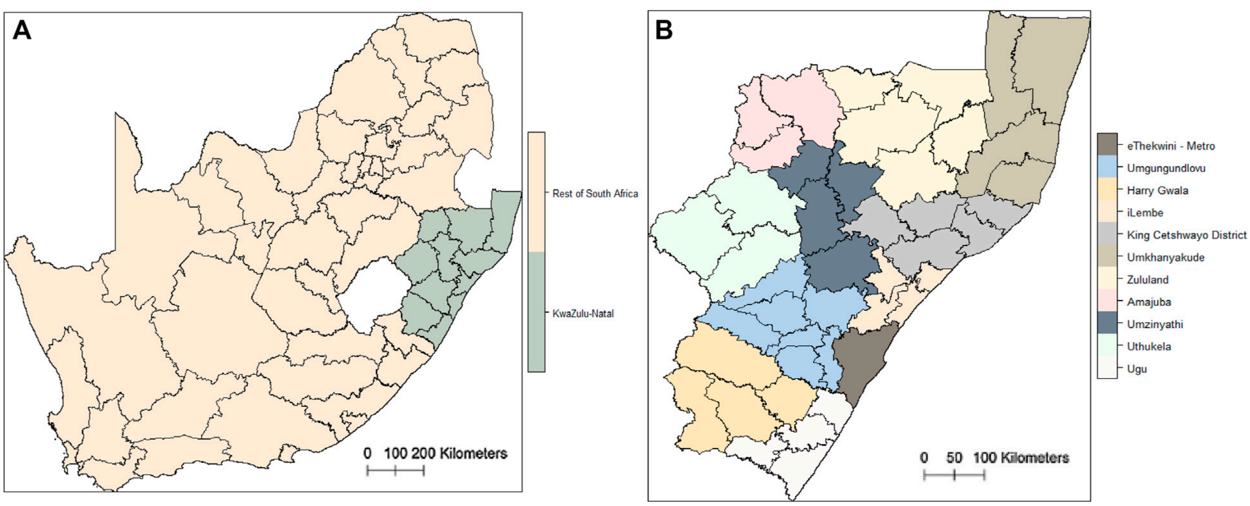

FIGURE 2 | (A) Location of KwaZulu-Natal in SA. District municipality borders are shown. **(B)** District municipalities in KwaZulu-Natal. Local municipality borders are shown. Data: Official shapefiles from the South African Demarcation Board (2016).

recent census was composed of Africans (86.8%), Asians (7.4%), Whites (4.2%) and Coloreds (1.4%). In most of the province, the main language is Zulu, alongside with Xhosa, English and Afrikaans (Stats SA 2012b). Politically, KwaZulu-Natal is divided into 11 district municipalities and 44 local municipalities (**Figure 2B**). This study uses the local municipality as main spatial unit of observation.

Historically, the arrival of the British in the 19th century initiated the enclosure of immense areas for sugar cane plantations that required large amounts of low-skilled labor. Colonization thus paved the way for today’s agro-industry and forestry. Sugar cane and timber plantations together are the dominating land use category in KwaZulu-Natal today and represent some 12% of the total land area (Driver et al., 2015). Next to this, degraded or fallow land represents some 8%, subsistence agriculture 7%, built-up areas 2% of total land cover. Land classified as “natural land” decreased from 66% in 2005 to 59% in 2008 (*ibid.*). KwaZulu-Natal is one of the few provinces in SA in which the rates of land use conversion loss are currently high enough to potentially irreversibly lose natural habitat within the next 3 decades (Driver, Sink, and Nel 2012). The threat of losing vital ecosystem services through land conversion underpins the relevance of choosing this geography with regard to their use by households.

The study relies on data from the “KwaZulu-Natal Income Dynamics Study (KIDS)”, the first ever collected set of panel data containing information on ES use based on questions regarding basic needs satisfaction of households. The data set followed an initial set of 1,519 households and spans back until before the end of apartheid in 1993 (University of KwaZulu-Natal 2004). For

TABLE 1 | Composition of the characteristic bundle of ES adopted from Hamann et al. (2015) for both census and KIDS data.

Number	Dummy variable	Observation (Dummy = 1, all other answers Dummy = 0)
1	*Animal production*	The household farmed one or more types of animals or poultry in the past year
2	*Crop production*	The household harvested one or more types of crops in the past year
3	*Natural building materials*	The household resides in a traditional dwelling (hut) made from locally available materials[a]
4	*Freshwater*	The household mainly sources its freshwater for household use from either a spring, stream or river
5	*Wood*	Wood as the main source of energy and/or average number of trips of at least one household member collecting wood per week ≥1

[a]*(Stats SA, 2012b, p. 19) define a traditional dwelling as "a dwelling made primarily of clay, mud, reeds or other locally available natural materials".*

selected variables, KIDS data is comparable to the second data source, national census data from 2011 (Stats SA, 2012b). In South Africa, census data is collected every 10 years with an expected next release in 2022, a year in which this analysis could potentially be updated. Using both data sources permits the study to observe not only the distribution of different types of SES but also ES use dynamics within each type of system. The data sets are representative at the respective level of aggregation and population weights have been used to calculate the results. Lastly, the results from survey data are mapped and spatially represented using the most recent and official shapefile data downloaded from the South African Demarcation Board (2016). Note that several municipal border changes inhibited a consistent spatial analysis of KIDS data.

Understanding Regime Shifts From Direct Ecosystem Service Use in Social-Ecological Systems

We propose to use household-level data on direct ES use as a proxy for the underlying dynamics of SES building on the premise that there exist characteristic bundles of ES that represent "integrated expressions of different underlying social-ecological systems" (Hamann et al., 2015, 218). A similar bundle has been chosen from 2011 census data according to local circumstances and data availability by these authors reflecting vital basic needs, including variables that indicate how food, energy, shelter and water are accessed (**Table 1**-Composition of the characteristic bundle of ES adopted from Hamann et al. (2015) for both census and KIDS data.). The main difference is that in several cases, KIDS data is more detailed. For instance, in the KIDS data set, additional information exists on the frequency with which households self-collect wood per week as well as the number of household members engaged in self-collection of wood. Conversely, census data only indicates the main source of energy for cooking or heating, among "wood" is one out of several possible sources. In such cases, the minimum common denominator between the two datasets has been chosen with regards to enhancing consistency across data waves.

ES use data are assumed to be expressive of the metabolic relationship each household[2] with their surrounding ecosystems. Such metabolic relationships can be indicative of variegated relational forms between the human and non-human counterparts of a system, including cultural, spiritual or economic relationships. Uses of other ES are likely to be correlated with the use of the five ES but cannot be included in the characteristic bundle due to the lack of purpose-collected data. Indeed, many studies underpin the importance of hundreds of wild resources as significant components of livelihood constituencies in Sub-Saharan Africa, especially in rural areas (Cavendish 2000; Shackleton and Shackleton 2011; Neves 2017). Thus, the assumption also implies a higher likelihood that households which satisfy their basic needs with the chosen bundle of direct ES also make use of a larger basket of natural (or "wild") resources. This underpins the characteristics found for green loops. Conversely, in red loops the approach rests on the assumption that non-use of direct ES implies the reliance on distant ecosystems. As a corollary, red loop dynamics presuppose an economic system able to extract, transport and distribute the ES necessary for basic needs, a high degree of the division of labor, a high degree of the regional or supra-regional integration of value chains as well as a potentially higher material-energy throughput of the system due to economies of scale and scope. A last necessary assumption for the approach taken is the premise that green and red loops form spatial units which are relatively coherent (Hamann et al., 2015). The scale of these units depends on spatial explicitness of survey data and the possibilities to cross-link ES use data with geospatial information. As described further below, in this study we use the local municipality as the spatial unit of observation, and analyze household characteristics of changing ES use within these units. The main premises of this approach are summarized in **Table 2**.

The type of loop is identified using a *kmeans* cluster algorithm which groups units (=local municipalities) with the highest average direct ES use into green loops and units with the lowest average direct ES use into red loops. Following Hamann et al. (2015), a third category of SES (so-called "transition loops") is included in the analysis in addition to green and red loops. The choice of three clusters was validated using the *clValid* package in R fitting the optimal number of clusters for comparability.

The procedure to identify loop types based on household-level use of the characteristic bundle of ES at local municipality level is as follows:

1. Determine the average share of households using individual ES (n = 5) at local municipality level (n = 44) and by year (n = 4)

[2]Defined as "a group of persons who live together and provide themselves jointly with food or other essentials for living, or a single person who lives alone. Note that a household is not necessarily the same as a family" (Stats SA 2011, 55). Note that KIDS has a similar, but somewhat looser definition of households.

TABLE 2 | Main premises of the methodological approach, including their rationale and potential limitations.

#	Premise	Rationale	Potential limitations
1	The use (or non-use) of a characteristic bundle of ES is expressive of the underlying dynamics of SES.	Households that do not (or only relatively little) use locally available ES *must* use distant ES (→ red loops) Households that use locally available ES relatively strongly *do not need* to use distant ES (→ green loops).	System configurations in which households use both locally available and distant ES can occur (AND/OR). Such a situation cannot be captured with the data available for this study which only permits a dummy variable (YES/NO) approach. Moreover, the available data does not permit to assess quantities of ES.
2	Loops correspond to clusters which form spatially coherent units.	The cluster algorithm attributes spatial units (i.e., municipalities) their loop “status” based on the average use “intensity” with which households use components of the characteristic bundle of ES (e.g., 71% of households in municipality A (green loop) self-collect wood for energy purposes which is sufficiently distinctive from municipality B (red loop) in which only 11% of households self-collect wood for energy purposes.	The goodness of the assumption depends on measures of dispersion of observations around the cluster points (the “intra-cluster variance”). In socially diverse or economically very unequal societies, households with fundamentally different means to access basic needs services live in spatial proximity. In such contexts, outliers are obfuscated by “labeling” a spatial unit green, red or transition loop. Thus, in red loops, green loop dynamics can persist, and *vice versa*.
3	Decreasing direct ES use can reflect a gradual regime shift.	Systems of provision in which the majority of households satisfies its basic needs by remote extraction of ES represents a fundamental re-organization of the previous system in which the majority of households relied on local ecosystems for basic needs satisfaction.	Concurring tendencies: Poverty or crizes can “push” households back to using local ES as a last resort; Educational efforts or conscious living can enable households in red loops to re-connect to the local biosphere, e.g., by perceiving local food, water or energy communities as a way of a convivial, resilient and diversified lifestyles.

2. Run a calibrated *kmeans* cluster algorithm to subdivide the 44 municipalities into clusters of high similarity: green loop (= high average use), transition loop (= medium average use) and red loops (= low average use) in the first year of the observation
3. Visualize the within-cluster change of average ES use in subsequent years comparing with the initial 1993 cluster solution
4. Spatially map the results of the analysis connecting geospatial data (official shapefiles) to spatial information contained in socio-economic survey data, where possible[3]

K means-clustering relies on the Hartigan-Wong algorithm (Wong and Hartigan, 1979). The algorithm minimizes the within sum of squares given by:

$$WSS(C_k) = \min \sum_{x_i \epsilon C_k} (x_i - \mu_k)^2$$

where *WSS* is the within sum of squares or total intra-cluster variance, *Ck* is one out of *k* ε {1,2,3} clusters, *xi* represents the individual data observation of a single municipality and *μk* the mean value of all municipalities clustered in *k*. The method picks random starting values for each of the groups (n = 25) and allocates individual observations to one of the three groups corresponding to the lowest *WSS* defined by numerical iteration (n = 10.000). By minimizing the *WSS* for each random starting point, the algorithm converges against pre-defined centroids that contain the least dissimilar observations. These centroids correspond to the amount of clusters (k = 3) based on internal and stability tests performed in the *stats* package in *R* as well as for comparison with Hamann et al. (2015). The distance between each centroid indicates the degree of similarity (or dissimilarity) between the three types of systems. As there is no predefined threshold (e.g. a minimum share of households that using an ES), the cluster algorithm will always find three solutions even if use intensities across all municipalities are comparable. Since we are interested in the question how average ES use intensities change over time *within* clusters, in subsequent section we use the kmeans clustering to identify the distribution of loop types in 1993–the first year for which ES use data is available. In a subsequent step, we analyze the average ES use intensities in subsequent data collection waves in 1998 and 2004 *within* the loops identified in 1993. This permits to observe the within-system dynamics of changing ES use which is illustrated by colored lines in **Figure 3**. The same figure indicates through stars the 2011 cluster solution as observed from census data for comparison. The line is not continuous since the 2011 value can only serve as a comparison. Due to limitations stemming from differences in the data structure (e.g., in sample sizes, geographical aggregation as well as questionnaires) we decided to use stars instead of a continuous line to indicate some reservation when comparing KIDS and census data.

RESULTS

Overall Trends and Characteristics Between 1993 and 2011

Direct ES use changed substantively in all three types of SES, green, transition and red loops, over the period between 1993 and 2011 (**Figure 3**). When interpreting these tendencies, it is important to keep the share of households per type of loop in

[3]Mapping local municipalities was only possible for the year 2011 (census data) due to shifting municipality borders between 1993 and 2004.

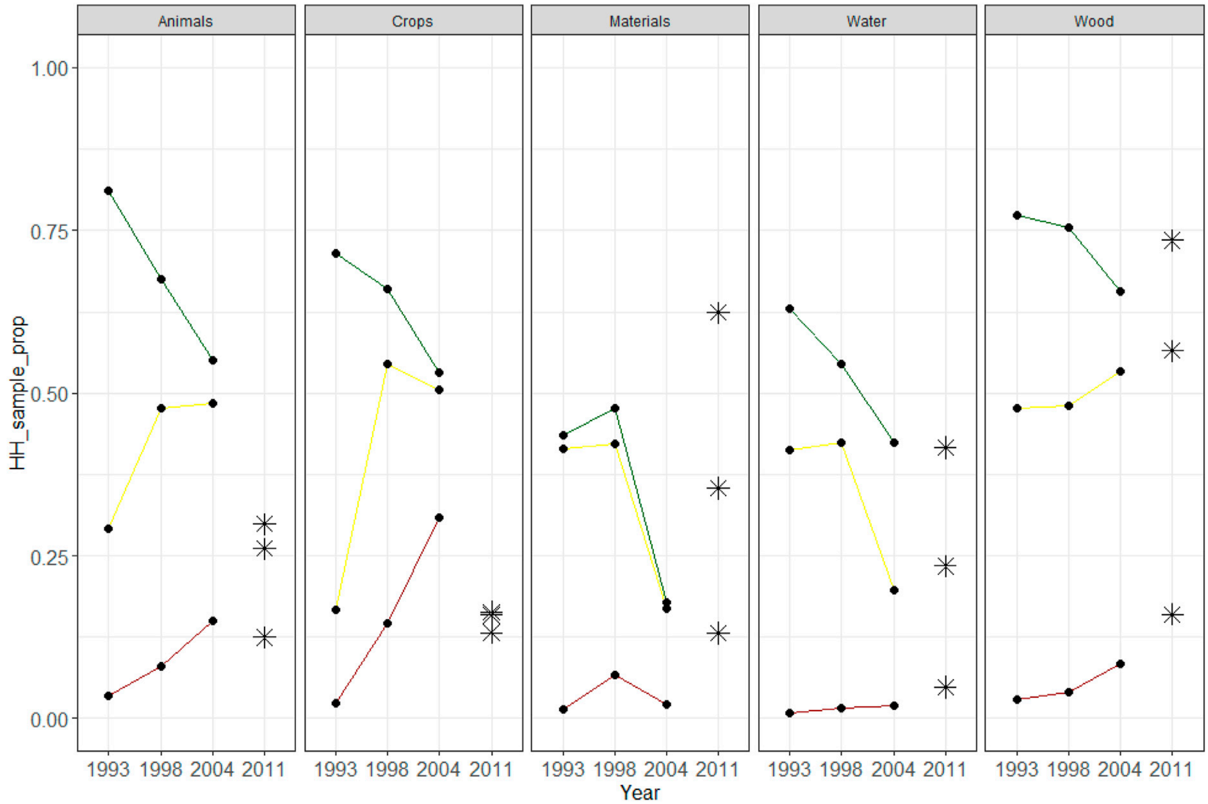

FIGURE 3 | Evolution of average direct ES use in KwaZulu-Natal between 1993 and 2004 at municipality level. Green lines correspond to green loops yellow lines to transition loops and red lines to red loops. Results from 2011 reported with stars for comparison. Standard errors (se) are within the range of se ε (0.008; 0.042). Data: KIDS 1993–2004 and 2011 census data. *Note: The analysis relies on the clustering of a municipality as green, transition or red loop in 1993 to observe changes within that municipality over subsequent data collection waves. Due to limited comparability between KIDS and census data and some inconsistencies seem apparent (e.g.*, "Materials" *where the data waves between 2004 and 2011 are not reasonably comparable).*

mind. In 1993, some 54% of all households in the KIDS sample were living in spatial units classified as red loops. Thus, more than half of the households in the sample already lived in red loops when the period of observation begins. By 2011, their share rose to 62% in 2011 in the census population. This potentially reflects the continuation of a gradual regime which has been ongoing since many decades. Moreover, in 1993, 16% of all households in the KIDS sample were living in spatial units classified as green loops, a share which decreased to 14% in the 2011 census population. Also, the share of households living in transition loops first increased from 30% in 1993 to 32 and 38% in 1998 and 2004, respectively, and drops to 24% in the census population in 2011.[4] Also this trend reflects the expected linear change away from green loops and toward red loops. However, non-linearities exist in the co-evolution of the type of loops. This is visible from several jump discontinuities in the graph, e.g., for the use of locally available natural building materials. More importantly, this can be seen in opposing tendencies of ES use between green and transition or red loops. While the average ES use in green loops drops, it augments at the same time in transition or red loops, especially for the variables concerning food (animal and crop production) and wood. That households *increasingly* use local ecosystems to satisfy basic needs in the case study area is underpinned by the fact that between 2005 and 2011 the land cover area in KwaZulu-Natal used for subsistence agriculture almost tripled (Driver et al., 2015).

With few exceptions, *k means* clustering identifies sufficiently dissimilar ES use across the three types of SES. This can be seen through the distance between the black dots (or stars, for census data) in each year of data observation. The black dots (or stars, for census data) indicate the average share of households using an individual bundle component in a respective cluster and year. One exception for poor variance across clusters is the US "crops" and "animals" in 2011, where we see that the share of households using this individual ES does barely vary across clusters. This may be explained by the fact that in South Africa there exists a separate census for agricultural households potentially rendering data quality in the standard survey comparatively poor.

The use of ES were found to correlate significantly with one another and we can reasonably expect that households using multiple components of the characteristic bundle of ES also use

[4]The absolute numbers and relative shares of sample households living in green, transition or red loops as well as the absolute number of clusters classified as either type of loop is provided in **Supplementary Table 1**.

TABLE 3 | Correlation coefficients between the five components of the characteristic bundle of ES.

	Water	Wood	Materials	Crops	Animals
Water	1	0.413	0.337	0.037	0.170
Wood	0.413	1	0.489	0.086	0.284
Materials	0.337	0.489	1	0.054	0.206
Crops	0.037	0.086	0.054	1	0.294
Animals	0.170	0.284	0.206	0.294	1

many more ES not comprised by the bundle (Hamann et al., 2015; Shackleton and Shackleton 2011). In KwaZulu-Natal, the strongest correlations in the KIDS panel data set were found between the use fuelwood and natural building materials (r = 0.49) as well as fuelwood and water from a natural source (r = 0.41). The least correlated is crop use with sourcing water from a natural source (r = 0.037). **Table 3** provides an overview of all correlation coefficients of bundle components as observed for KwaZulu-Natal from census data in the year 2011.

By Type of Social-Ecological System

In systems identified as green loops in 1993, the average share of households using direct ES from local ecosystems decreased consistently for all five components of the characteristic bundle of ES (**Figure 3,** green lines). Most notably, food-related provisioning services (animal and crop farming) and the use of natural building materials dropped over period of 18 years under observation. Locally sourced water and fuelwood use dropped less rapidly and remain on a comparatively high level in 2004 and 2011. In systems identified as transition loops in 1993, mixed tendencies are observed across the five components of the characteristic bundle of ES (**Figure 3,** yellow lines). Food-related ES (animal and crop farming) and locally collected fuelwood use become relatively more important to households' livelihoods, while natural building material use and water use from local sources significantly drop. The sudden surge of a food and energy-related provisioning services can indicate the exposure of households to food insecurity or economic hardship. In systems identified as red loops in 1993, also mixed tendencies occur across the five components of the characteristic bundle of ES, comparable to the tendencies in transition loops (**Figure 3,** red lines). Food-related ES (animal and crop farming) and fuelwood from local sources become relatively more important to households' livelihoods, while natural building material and water use from local sources are oscillating relatively little, remaining on levels of below 10% across all data waves.

By Type of Ecosystem Service

The importance of the characteristic bundle of direct ES for livelihoods varies. Clear tendencies can only be observed for the provision of drinking water and fuelwood. In all three types of systems, households decreasingly depend on natural sources for their drinking water. This is likely to be due to the increased supply of municipal tab water which has been one key pillar of urban and rural development strategies of post-apartheid South Africa. In the case of fuelwood, households seem to become increasingly reliant. Despite almost 78% of households using electricity for lighting in 2011 (Stats SA, 2012b), fuelwood continues to remain a very significant and increasingly important source of energy for cooking and heating. Across the three system types, fuelwood is used on average by 74% of all households in green loops, some 57% transition loops and some 16% in red loops. This mirrors studies that examine the continued strong use of fuelwood and in Sub-Saharan Africa (e.g., Dovie, Witkowski, and Shackleton 2004; Neves 2017). Given its importance, we conducted a first estimate of biophysical quantities of annual household use of fuelwood (**Table 4**). Provided that energy efficiency parameters, for instance, with regard to cookstoves, did not significantly change over the observation period, we assume that the total annual fuelwood consumption is strongly correlated with population growth which was between 1996 and 2011 more than 20% (Stats SA, 2012b). Moreover, the results in **Figure 3** indicate that the share of households using fuelwood as primary energy source increased since 1993, especially in transition and red loops.

Natural building materials are decreasingly used to a lesser extent across all types of systems. The sudden drop of households indicating to live in dwellings made of locally available materials in 1998 however is due to a data inconsistency between KIDS and census data. Due to the higher representativeness, census data should ultimately be preferred for interpretation and it is likely that KIDS underestimated the number of households living in dwellings made of locally available materials. Moreover, food-related direct ES have seen a strong decrease in green loops and opposed to that, an increasing trend in transition and red loops. This is interesting in so far as that while in green loops self-grown food decreases in relative importance, in transition and red loops, they strongly increase between 1993 and 2004 and approximate levels comparable to green loops. Comparing the KIDS data to census data is also here possible only with reservation. Yet, given that red loops and transition loops represent over 65% of the total land area of KwaZulu-Natal, the finding is consistent with the most recent physical account of land cover change between 2005 and 2011 which showed that subsistence agricultural land increased almost by a factor of three between 2005 and 2011. Moreover, the increasing share of subsistence agriculture in red loops may be interpreted as a rising interest in urban agriculture, a trend found of particular relevance in urban townships (Coetzee and Van Averbeke 2011).

Which ecosystem services in which spatial unit are used is a function of biophysical supply of ES and socio-economic and political factors (SRC 2011; Biggs et al., 2012). The combination of these factors eventually defines the properties of the emerging system. In KwaZulu-Natal the biophysical supply of ES varies across municipalities (SANBI 2018). This variance highlights another limitation of our approach which implicitly assumes an equal distribution of biophysical supplies across KwaZulu-Natal. This is because we define the characteristic bundle of ES uniformly across all municipalities, regardless of whether analyzing the mountainous hinterland with continental climate of the province or the coastal belt with milder climatic conditions. Hamann et al. (2015) use additional variables like the local supply of wood, the mean annual runoff of water and the grazing and

TABLE 4 | Estimate of annual fuelwood consumption in KwaZulu-Natal.

	Share of total households using fuelwood as primary energy source by loop type (%)	Number of households using fuelwood as primary energy source by loop type[a]	Aggregate fuelwood consumption per year (tons/year)[b]	Estimated emission levels (Megatons carbon dioxide/year)[c]
Green loops	73.50	316.693	1.161.630,4	1,54
Transition loops	56.50	435.388	1.597.004,8	2,12
Red loops	16.00	317.122	1.163.203,2	1,55

[a]*This figure includes agricultural and non-agricultural households for which separate census data is available.*
[b]*This figure was calculated using a comparable default on average fuelwood consumption per capita validated by UNFCCC (2019) for use under the Clean Development Mechanism in Ethiopia (=0.917 tons/year). The figure was calibrated at household level in KwaZulu-Natal (provincial average household size in 2011 = 4.0 persons/household).*
[c]*This figure was calculated using a comparable default on the fraction of non-renewable biomass validated by UNFCCC (2019) for use under the Clean Development Mechanism in Ethiopia (=0.76), IPCC default parameters on emissions from burning woody biomass (112.000 kg/TJ) and the net calorific value of fuelwood (0,0156 TJ/ton).*

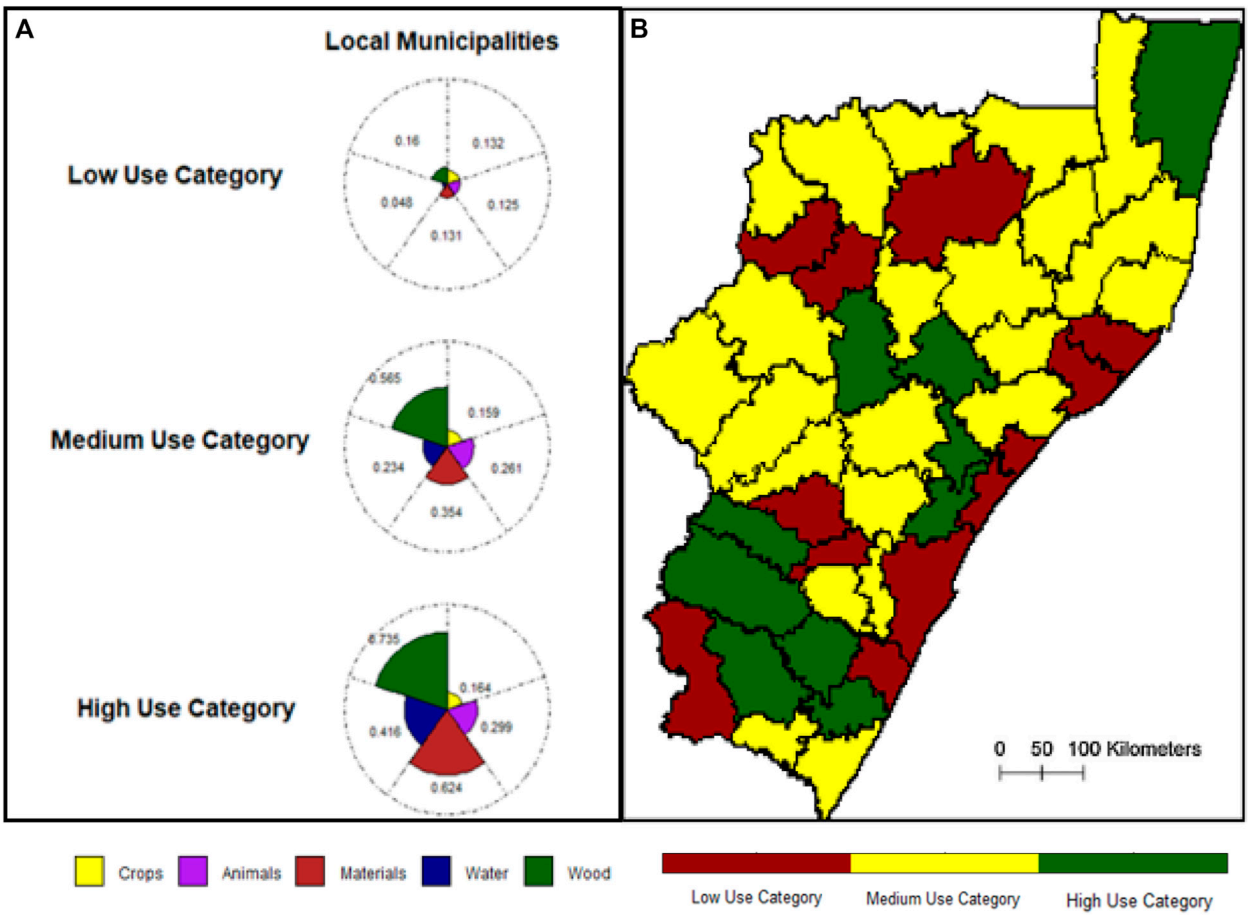

FIGURE 4 | (A) Typical composition of direct ES use at municipality level. Low use category corresponds to red loops, medium to transition loops and high to green loop types of SES. Petal lengths indicate the average percentage of households in a given category using one direct ES. Standard errors (se) range within se ε (0.008; 0.042). **(B)** Distribution of use categories across KwaZulu-Natal. Data: Census 2011 and official shapefile data for border demarcation.

cultivation potential of municipalities to predict the type of loop with biophysical supply factors. This type of analysis could also be extremely valuable, especially when linking the question of the *quality* of biophysical supplies to dynamics of green or red traps. With the data available for this study, we only conducted an additional analysis to predict the ES use intensity from social factors (e.g., household income, gender of household head etc.). Since this type of causality analysis is not the focus of this paper, the preliminary results are presented in **Supplementary Table A2**.

Spatial Distribution of Loop Types in 2011

The compatibility of census data with recent border demarcation in KwaZulu-Natal permits to associate green, transition and red loops with shapefile data from the South African Demarcation Board (2016). Spatially mapping SES assumes that it possible to assign clear spatial boundaries to SES whereas in reality boundaries in complex systems are likely to be less pronounced (Cilliers 2001). The emerging map of green, transition and red loops shows a clear non-random pattern of distribution in 2011 (**Figure 4**). Green loops appear in clusters in the north, center and south of the province while red loops dominate in the most populous coastal areas. In KwaZulu-Natal, green loops visibly overlap with the distribution former *bantustan* or homeland areas of South Africa where Zulu or Xhosa people were forcefully settled as an act of racial segregation by the apartheid regime (**Supplementary Figure 1**). Of the total number of households, 62.26% of all households in KwaZulu-Natal live in red loops, 24.21% in transition loops and 13.53% in green loops (**Supplementary Table 1**). This corresponds to 15, 25 and 11 local municipalities, respectively. Further research demonstrated that human wellbeing in green loops tends to be lower than in red loops (Hamann et al., 2016).

The different geographical aggregation of KIDS panel data as well as several shifts in local and district municipal border demarcation between 1993 and 2011 made it impossible to spatially map the changing types of systems over time. This is why spatial mapping could only be performed for 2011 census data. Changes in ES use could well be mapped with upcoming 2022 release of census data.

DISCUSSION

This study observed the relationship of households with surrounding ecosystems based on analyzing the changing use of a characteristic bundle of ES relevant to satisfy basic needs over time. Embedded in the green-to-red loop transition model, in three main aspects are discussed. First of all, this concerns the empirical limits and possibilities of identifying a regime shift using a characteristic bundle of ES as a proxy. The second section discusses the assumptions and limitations of the analysis. The third section discusses the underlying drivers of change based on existing research. The fourth section discusses the potential of using this approach as an entry point to study the diverse relationships between humans and ecosystems in the context of transformative change toward safely and justly staying within planetary boundaries.

Green-to-Red Loop Transition: Has a Regime Shift Occurred?

The term regime shift is repeatedly used to describe processes within social-ecological systems that fundamentally alter the organization of underlying system dynamics (SRC 2011; Biggs et al., 2012). The exact meaning of such fundamental change strongly depends on the definition, the scale and scope of the system under investigation and therefore notably on the theoretical and methodological choices in the context of a specific case study. This study examines a substitution process where locally sourced ES get increasingly replaced by faraway indirect ES in the case study area of KwaZulu-Natal (**Figure 3**). We found that in green loops identified in 1993, the average use of ES consistently dropped across all ES composing the characteristic bundle. In transition loops, the tendencies are rather mixed and in initial red loops, the average use of several ES even increased throughout the observation period. Given this mix of tendencies, we argue that more scientific effort is needed to calibrate thresholds upon transgression of which one can robustly identify a regime shift. This should take into account sufficient leeway for non-linearities to account for increased pressures in red loops on local ecosystems, e.g., local forests or locally available arable land in times of crisis.

However, in our view, the substitution process of locally sourced direct ES by faraway sourced indirect ES can very relevantly underpin the understanding of regime shifts and provide an important entry point to studying the relational shifts between societies and their natural environment in SES research. In the past, this process was typically geared from green to red loops, i.e., from strong reliance on local ecosystems toward the remote extraction of ES (Cumming et al., 2014). Gradual regime shifts presuppose that slowly changing variables within a system entail its fundamental re-organization. Despite the uncertainty on thresholds, we acknowledge from the empirical observations that red loop dynamics increasingly take precedence over other type of loops in the case study area. This implies an entire set of historically specific variables to change within that process, including infrastructural provisions, increased division of labor, integration of local economies into global value chains of certain locally available ES and many more. These dynamics reflect the history of humankind which is so far, in brief, the transformation from hunter-gatherer societies to urban-industrialized ones. Globally, this process has taken place over the course of millennia, and was only relatively recently accelerated through agricultural and industrial revolutions, as well as globalized in an initial stage through colonization and trade (Cumming et al., 2014). While sub-Saharan Africa has a millennia-long history of trade, remote extraction of ES necessary for basic needs likely only commenced with South Africa's largely coal-driven electrification as part of a gradual extension of trade and service infrastructure since the end of the 19th century. Today, coal-fired electricity generation continues to represent about 70% of total installed capacity (IEA 2021). With consumption mainly stemming areas where the majority of household and industry demand are located, red loops are thus the main drivers of South Africa's energy-related greenhouse gas emissions which continue to be unaligned with the objectives of the Paris Agreement even in light of stated policies under its updated nationally determined contribution (CAT, 2021). Also in green loops, burning locally collected fuelwood for cooking and heating contributes to global climate change through increased deforestation and a reduction of the net carbon stock of the country (see **Table 4**). Depending on the type of loop, the energy sector poses different sustainability management challenges and risks to enter into trap dynamics.

Furthermore, the increase in reliance on fuelwood in transition and red loops buttresses research on unequally distributed access to a reliable and affordable electricity grid as well as local ecosystems as 'provisioning systems of last resort', e.g., in times of crisis (Shackleton and Shackleton 2011; Baker and Phillips 2019).

In summary, our findings illustrate a critical fraction of a systemic transformation of basic needs provisioning systems in South Africa which is ongoing since decades. However, we believe that the speed of change in the observation period in post-apartheid South Africa is substantively to be higher compared to previous decades. The findings support the view that the case study area of KwaZulu-Natal is a highly heterogeneous landscape in which different types of social-ecological systems co-exist and co-evolve over time (**Figure 3**). We call for future research defining comparable thresholds for the speed of change from green loops (=local ES use) to red loops (=distant ES use) as a regime shift as well as on second-order conditions for "trap dynamics", e.g., derived from downscaled frameworks on planetary boundaries or doughnut economies (e.g., Cole, Bailey and New 2014; Raworth 2017) and tipping elements (e.g., Lenton et al. 2008; Otto et al., 2020). Partially reflecting these ideas studies in the context of regime shifts already exist in food or energy production and distribution systems (McMichael 2009; Hamann et al., 2015; Pereira et al., 2020).

Assumptions and Limitations of the Analysis

The expressiveness of the selected characteristic bundle of direct ES represents an important underlying assumption to infer system dynamics based on its use or non-use. We argue that while it represents a first-best and context-appropriate measure of the immediacy with which a household depends on local ecosystems, more comprehensive data is needed to include and tailor-make characteristic bundles of direct ES for case study areas. This may include differentiations between the rural-urban nexus, but also North-South differences of application. At the same time, more research is needed on the expressiveness of non-use of direct ES, which in our analysis, indicates that households rely on distant ES brought by to the site of consumption through market-based means of exchange. Across all loops, direct ES use can be seen as expressive not only of the economic status and social vulnerability of the household, but also of its cultural, historical and spiritual connection to (or disconnection from) local ecosystems. However, further qualitative inquiry would be needed to study potentially differing subjective perceptions of local environments between loop types and direct ES uses, sentiments of responsibility or of spiritual closeness to the biosphere. One strict limitation of this study is the sole use of secondary data. With exception on the use of fuelwood, for which default data could be used to quantify an estimated material-energy throughput of woody biomass, the use quantities of the different bundle components could not be analyzed as part of this study. This, however, could highly be relevant, e.g., in relation to increased purchasing power and related rebound effects, especially in urban areas.

We furthermore identify relatively coherent spatial units based on municipality-wide averages of household-level use of direct ES. This assumption reflects archetype analysis which aims at identifying recurrent patterns across similar types of systems (Eisenack et al., 2019). However, as anticipated above, it likely obfuscates relevant intra-cluster differences between households, especially given the pronounced socio-economic inequality present in South Africa. Knowing that predominantly social factors predict the use intensity of direct ES at municipality level (**Supplementary Table A2**), more research would be needed to estimate the robustness of using municipality-wide averages of household-level use of direct ES as proxies for more aggregate SES dynamics. Using this approach however is highly useful, e.g., to formulate spatially targeted policies in the domain of land use policy, sustainability management or common pool governance strategies (Ostrom 2007; Hamann et al., 2015; 2016).

As described above, this study does not use an ex-ante determined threshold (e.g., an average percentage or range) that once transgressed, marks a regime shift i.e., the transition from a green to red loop. Rather, the classification of the type of social-ecological system was guided by *kmeans* clustering which grouped average ES use data from local municipalities into a pre-determined number of groups. The number of centroids should depend on internal or stability measures that provide an optimal number of clusters, corresponding to green, transition and red loops (Hamann et al., 2015). For KIDS data, also three was chosen as the number of centroids for which stability measures scored highest, however not across all ES (e.g., crop farming). Using clustering is a common method to study social-ecological systems (e.g., Janssen et al., 2012). Cluster algorithms come with trade-offs when comparing results to potential future studies in the field. This stems from the fact that *kmeans* clustering uses relative measures of proximity. This allows to group spatial units into clusters of highest similarity within one heterogeneous geography. However, more comparative research in the field would be necessary to derive absolute thresholds from similar bundles of ES use to form common benchmarks. Moreover, one further limitation of the analysis is that we cannot take into account migratory activities based on the KIDS or census data, despite evidence that the period of observation experienced significant migration. That migration plays a role is illustrated by KIDS data which follows household heads from 1993 to 2004. The possibility that these households have moved from urban areas (=likely red loops) back to rural areas (=likely green loops) at the end of the survey period is reflected by linkages of urban labor markets with rural areas and the common practice for aging South Africans to spend their pension life in rural areas with family roots (**Supplementary Table A2**).

Understanding Underlying Drivers of Change

System properties emerge as a function of biophysical supply of ES and socio-economic and political factors relating to their governance (SRC 2011; Biggs et al., 2012). Hamann et al. (2015) have found that, in South Africa, social factors predominantly predict the type of social-ecological systems, including household income, high proportions of female household headship and land under traditional tenure. Ecological supply factors, such as the mean annual run-off of water, grazing land potential or the supply of wood, have been found to only partially explain high direct ES use patterns (*ibid*.). This insight is crucial for understanding the use dynamics within green, transition and red loops. For KIDS data, panel regression analysis partially confirms these findings, where the availability of data permits to do so (**Supplementary Table A2**). Factors determining land access, and with that, direct ES use warrant separate analyses in the context of the complex agrarian political economy of South Africa and its failed land reform (Aliber and Hart, 2009; Cousins, 2010; Cousins, 2017). Indeed, land grabbing and forced removals of indigenous populations mark the most important contributor to changing dynamics in social-ecological systems over the last 350 years (e.g., Platzky and Walker 1985; Cousins 2017). That large parts of areas in KwaZulu-Natal identified as green loops overlap with the former homeland areas of South Africa is telling of the fact that using the characteristic bundle of direct ES is an indicator of social vulnerability and deprivation. Although direct ES use decreases in these areas continuously, it remains relatively high across all five direct ES, especially in the category of energy supply through local fuelwood uses, and also for drinking water from natural local sources. The dynamics of direct ES use supports the argument that in South Africa local ecosystems are a safety nets in the absence of a welfare state (Shackleton and Shackleton, 2011; Neves, 2017). This may especially be important in old age or times of crisis. Examining for instance, to what extent the lockdown of critical basic needs infrastructure during the covid-crisis pushed South Africans to increasingly use ES would be highly interesting to examine, including in combination of studying problems of overuse and undersupply of local ES. The methodology applied here can only identify the dynamics and the distribution of ES use. However, it cannot explain the drivers of change, i.e., underlying causalities of regime shifts. This remains an important area for future research.

Associating underlying causalities of change by empirical analysis could furthermore help to explain not only the past evolution of system transformation over time but can also help understand future barriers to transformative change. Next to socio-economic and biophysical standard data surveys, such an analysis needs to take into account the political economy of transition processes. Indeed, questions of power, history and class have not received much attention in transdisciplinary sustainability research, even in ecological economics (Pirgmaier and Steinberger 2019). Especially in the case of land access and agrarian reform in South Africa, such inquiry is certainly apt (Cousins 2010). This is why we call for studying the political economy of green or red loops as a future research avenue to enhance a better understanding of barriers to profound transformative change in SES.

Identifying and Mapping Social-Ecological Systems as an Entry Point to Studying Transformative Change

We identified and mapped SES based on the use of a characteristic bundle of five direct ES and examined changing direct ES use patterns over time. It was shown that this approach provides a heuristic to observe and understand the past evolution and current distribution of different types of SES. We argue that this transition model cannot only be deployed descriptively, but also forward-looking in a normative setting (**Figure 5**). Sparking social-ecological transformation toward more sustainable futures may require “fundamental shifts in perspectives, world views and institutions” (Folke et al., 2011, 719). This can include for instance participation in initiatives that aim at reconnecting people with the biosphere (Hamann et al., 2015; Pereira et al., 2020). Such initiatives notably explore the possibilities of re-localizing and de-centralizing food and energy provisioning systems (*ibid*.). In the case of food production regimes for instance, Pereira et al. (2020) find that enhanced certification and labeling of food products as a key innovation to spur transformative change through alternative food networks independent of anonymous global supply chains. Moreover, community-supported agriculture (CSA) projects can approximate producers and consumers and increase consciousness of the origin of food products. Increasing recognition of traditional agroecological knowledge can help to respond to pressing sustainability challenges of current agro-industrial food system (e.g., Guerrero et al., 2019).

Purpose-collected data could help to build more detailed characteristic bundle of direct ES used for identifying and mapping transformative change at societal level. With purpose-collected data, it would be possible to differentiate between the *quality* and *intention* of ES use, which, in combination with more disaggregated geospatial and biophysical data could provide an excellent basis for identifying social and ecological deprivation on the one side, and on the other, seeds of transformative change (**Figure 5**). This could help to enrich the loop transition model and distinguish sustainable loops from unsustainable ones. Moreover, the use of additional variables as part of characteristic bundles of ES use could further expand the expressiveness of underlying relationships of households with ecosystems.

CONCLUSION AND RESEARCH OUTLOOK

In this paper, we explored the concept of regime shifts based on direct ES use of households in the context of the green-to-red loop transition model. First of all, we observed a clear tendency of changing systems of provision for basic needs in the transition from green to red loops. This analysis was based on decreasing use of a characteristic bundle of direct is ES. This is indicative of a gradual regime shift, however, the absence of comparative studies and quantified thresholds hindered the conclusive identification of a regime shift. Moreover, such insight likely requires longer observation periods than the 18 years observed between 1993 and 2011 in this study. The research however shows important dynamics of how direct ES use non-linearly evolves over time and to what extent locally available ES continue to be of significant importance today, even for livelihoods in red loop type of systems. We furthermore identify the spatial distribution of SES in 2011 similar to the analysis by Hamann et al. (2015) at provincial level in the case study province of KwaZulu-Natal. Based on the empirical

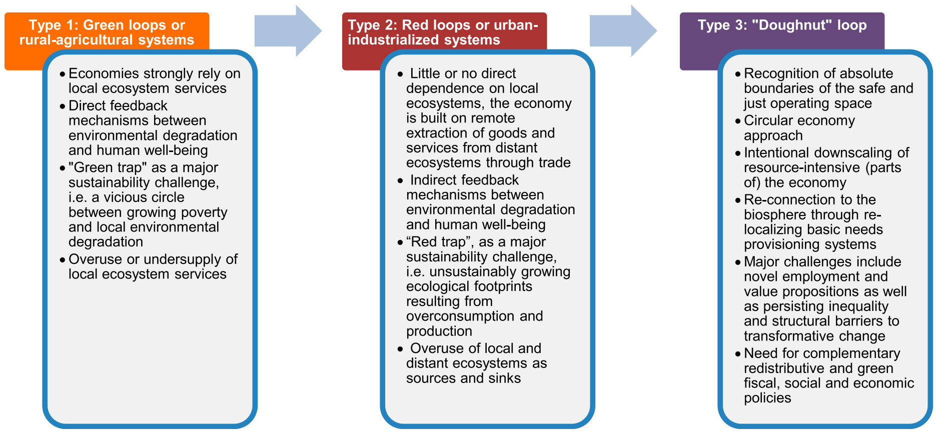

FIGURE 5 | The expanded loop transition model. Adopted from Cumming et al. (2014) and Raworth (2017).

results of the analysis, we discussed general aspects relating to the study of regime shifts in the context of the green-to-red loop transition, including the questions how to identify thresholds which apt to determine the frontier between one and another type of system. In addition to that, the results are discussed in the context of existing research on factors determining the transition between green and red loops and points at the importance of perspectives of agrarian political economy for understanding the history and status quo of land access in South Africa. Indeed, what the paper cannot achieve is distinguishing between the qualities and intentions with which households access direct ES, an aspect that could with purpose-collected data be an excellent opportunity for further study of regime shifts in the context of system transformation. Owing to its holistic nature and high adaptiveness to different geographical and cultural contexts, there exist many potential future research avenues. This includes for instance identifying and mapping social-ecological systems based on different compositions of characteristic ES use bundles, combinations with local or regional doughnut economy indicator frameworks or illustrations of emerging alternative food or energy production networks.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article are available under the links provided in the references University of KwaZulu-Natal (2004) and Stats SA (2012b).

ETHICS STATEMENT

The authors used secondary and anonymized data. Therefore no ethical approval was needed to include the observations in this study.

AUTHOR CONTRIBUTIONS

Conceptualization, methodology design and data analysis were part of the corresponding author's master thesis to which IO acted as supervisor of.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2021.695348/full#supplementary-material

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The Heterogeneous Impacts of Human Capital on Green Total Factor Productivity: Regional Diversity Perspective

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That human capital improves the efficiency of Green Total Factor Productivity has been established in research fields, but the heterogeneous effects of human capital on GTFP and its sustainable mechanisms are unclear. This study examines the effects of human capital accumulation, fiscal spending on education, and innovation on GTFP efficiency under spatial and temporal diversity. Employing panel data from 30 provinces from 2001 to 2018 in China, we analyzed the dynamic and static efficiency of GTFP in different regions by three-stage data envelopment analysis (DEA). The heterogeneous effects of human capital on GTFP were explored through Tobit regression. Results reveal that the average value of GTFP efficiency is an inverted U-shape and the presence of significant t geography differences. Human capital accumulation and fiscal spending on education have positive effects on GTFP efficiency; however, innovation negatively affects it. At the same time, marketization growth decreases the positive influence of human capital and education on GTFP efficiency. While, this effect was not observed regarding innovation, the implication of these results concerning the human capital heterogeneous effects of GTFP efficiency in a different geographic context. Establishing a fair and transparent system can reduce the endowments gap and effectively promote GTFP efficiency in developing countries.

Keywords: green total factor productivity, heterogeneity human capital, innovation, FDI, environment policy

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INTRODUCTION

Around the world, large-scale urbanization has brought about a series of challenges for the human living environment (United Nations Department of Economic and Social Affairs, 2016), such as extensive pollution, energy crisis, and ecological imbalance (Patwa et al., 2021). Under this new governance framework, resources can be reconfigured to extract more value by reducing pollution emissions (Hobson, 2021). Ecological imbalance and high pollution emissions in developing countries have attracted international environmental concerns (Eskeland and Harrison, 2003; Golini et al., 2018). As the largest developing country, China's total energy consumption reached 4.98 billion tons, showing year-on-year growth of 4.3% by 2020. Thus, China has been working on "high emissions, high pollution, and low efficiency" (Sun et al., 2019). Green total factor productivity (GTFP) is an essential concept that requires the reduction of energy consumption and environmental pollution. Similarly, it is also an essential tool to measure the green economic performance of industries. Compared with traditional total factor productivity (TFP), which ignores the environmental pollution

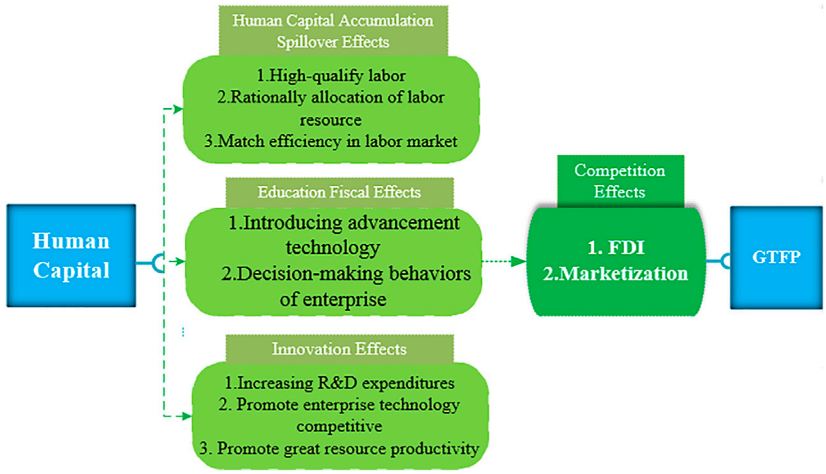

FIGURE 1 | The sustainability mechanism of human capital on GTFP.

cost of GDP growth, GTFP considers energy consumption and environmental factors (Jin et al., 2020).

The majority of the literature focuses on measuring the index of GTFP. Huang et al. (2020) measured GTFP through the dynamic panel generalized method of moments (GMM) model. Chen and Zhou. (2017) added industrial "three wastes" into the output factors and then measured the environmental efficiency of 11 provinces in China's Yangtze River Economic Belt. Ji et al. (2019) adopted the data envelopment analysis (DEA) method and determined that the efficiency of pollution treatment and waste disposal technology in Eastern China was the highest, while the technology levels in Western China were the lowest. Numerous studies focus on the micro or macro-economic policies evaluation, including the trade (Mary and Konings, 2007; Loecker, 2011; Sahoo et al.,2018; Jiang et al., 2021; Jiang, 2021) and industrial agglomeration policies (Martin et al., 2011). GTFP methods break down mathematical programming techniques (DEA) or econometric modeling (Stochastic Frontier Analysis, SFA). Beeson and Husted (1989) use DEA to investigate the differences in the U.S. sectoral efficiency. Some studies evaluate GTFP in China. For example, Song et al. (2018) investigate the impact of China's "new normal" economic development policy on environmental technology advancement and industrial land-use efficiency. They argue that weak environmental regulations have no significant impact on environmental technology advancement, while new normal economic policies improve industrial land efficiency. Other research measures GTFP through enterprise microdata. Zhu etal. (2018) employ DEA to evaluate China's mining and quarrying industry. They demonstrate that technical progress is the major driving factor of the production progress in this sector. Based on the above, we conclude that scholars are still interested in topics concerning GTFP, especially policy evaluation and industrial production driving factors. However, few studies combine human capital and policy evaluation to analyze China's provincial GTFP.

Figure 1 illustrates the sustainability mechanism of human capital on GTFP efficiency. We argue that human capital has an impact on GTFP from two paths: first, the direct mechanism is through human capital accumulation, fiscal education spending, and innovation effects. Second, the indirect mechanism is through system shock (e.g., foreign capital entry and increased marketization level), which leads to competition effects that indirectly improve the human capital effects on GTFP.

Human Capital Spillover Effects. In terms of economic growth, the manifestation of human capital spillover effects includes higher labor productivity, rational allocation of labor resources, and decreasing labor market mismatch. On the other hand, human and physical capital have substitution effects. It means the marginal return of human capital declines more slowly than material inputs. Ang et al. (2011) suggest that human capital could improve productivity by optimizing other factor structures. Furthermore, the current study expects that human capital directly influences GTFP by increasing labor productivity and other input factor productivity (James et al., 2011). However, the literature ignores the geographic variety, particularly in China—a country with unbalanced economic development. Some research indicates that the level of human capital effects on GTFP varies greatly under regional disparity (Vandenbussche et al., 2006). Theophile et al. (2009) emphasize that medium-quality human capital is more critical to TFP than high-quality human capital in a relatively economically underdeveloped city. The possible explanation is that the improving TFP is caused by imitating technologies of economically developed areas, rather than innovation.

Education Fiscal Spending Effects. China's regional diversity affects the disparity of GTFP between provinces for a long time. The central government has increased fiscal education spending for technology and knowledge to reduce inter-regional variability. Some literature argues that R&D and education, such as the endogenous decision-making behavior of enterprises and residents, are likely associated with fiscal education spending effects. Human capital and technological advancement in backward areas may promote economic growth and narrow the regional economic gap (Viaene and Zilcha, 2002; Glomm and Ravikumar, 2003). However, some studies find that government education spending has a significant effect on economic growth in developed countries but has no significant impact in developing countries (Blankenau et al., 2007).

Innovation Effects. Innovation is one of the essential knowledge-intensive activities enterprises engage in through increasing R&D expenditure to obtain advanced technology. If technology coverage is fully maximized in the market, a technology monopoly can be realized, and this can help enterprises obtain surplus profits. This behavior promotes the improvement of regional innovation and achieving human capital accumulation (Collard-Wexler and Asker Locker, 2012). Simultaneously, enhancing the regional innovation level promotes enterprise technology competition to promote long-term social development. For example, new technology applications, artificial intelligence, and energy-saving technology have dramatically reduced energy consumption. Moreover, material innovation promotes great resource productivity, which formats the sustainability loops of "R&D-production-market-sales" (Cheng, 2021). Meanwhile, it also reduces the possible environmental pollutants during the organization's activity. Under the technology spillover effects, resource optimization urges enterprises to eliminate outdated production capacity and improve resource utilization efficiency, contributing to the regional green economic development. However, the technology with high investment and risk increasing the threshold for the market. Because spillover effects may not affect the downstream and upstream chain, several weak technological enterprises may increase the resource investment to compensate for their technological disadvantages. It results in a decline in the region's overall resource utilization efficiency, which is not conducive to circular economy development. Drawing on the above, the following hypothesis is proposed: Human capital, fiscal education spending, and innovation show heterogeneous influence over GTFP.

The rest of the paper is outlined below. *Materials and Methods* describes the econometric method, including data and variables. *Results* includes the empirical analysis; *Discussion* further discusses the mechanism of GTFP; and *Conclusion* sums up the conclusion.

MATERIALS AND METHODS

Calculation of GTFP

We calculated these values to measure the principle-level evolution of the GTFP from 2001 to 2018 in China through three-stage DEA models. Compared with the two-stage DEA model, the entry input-output system is a black box, thus ignoring the specific production and operation processes; the three-stage DEA explores the intersystem and distinguishes between the different factor effects. The model steps are as follows: the first stage uses the DEA-BBC (Banker, Charnes, Cooper) model, introduced by Banker et al. (1984), to separate and estimate technical and scale efficiency in the DEA. The model equation is as follows:

$$\begin{cases} \min = \left[\theta - \varepsilon\left(\hat{e}^{T}S^{-} + e^{T}S^{+}\right)\right] \\ \text{s.t.} \sum_{j=1}^{n} \lambda_j X_j + S^{-} = \theta x_0;\ \sum_{j=1}^{n} \lambda_j y_j + S^{+} = \theta y_0;\ \sum_{j=1}^{n} \lambda_j = 1; \end{cases} \quad (1)$$

In **Eq. 1**, the j = 1, 2...n is defined as the number of decision-making units. The input and output elements are X_j and Y_i, respectively, and the value of λ_j is defined as the combination coefficient of the decision-making unit; e^T is the unit row vector; θ is the value of the decision-making unit; S^+, S^- represent the surplus variable and slack variable, respectively. If $\theta = 0, S^+ \neq 0$, or $S^- = 0$, the decision-making unit is efficient. If $\theta < 0$, the decision-making unit is inefficient.

According to the study of Aigner et al. (1974), we evaluated the efficiency through SFA (Stochastic Frontier analysis) model at the second stage. Fried et al. (2002) claim that the decision-making unit is affected by management inefficiencies, environmental effects, and statistical noise. The slack variable can reflect the initial low efficiency, constructing the SFA model to show regression of the first stage variables with environmental variables and the mixed error term. The SFA model is as follows:

$$S_{ni} = f\left(Z_i; \beta_n\right) + \nu_{ni} + \mu_{ni};\ i = 1, 2, \ldots, I;\ n = 1, 2, \ldots, N \quad (2)$$

In **Eq. 2** S_{ni} represents the decision-making unit i on Slack value of n; and Z_i represents environment variables; $\nu_{ni} + \mu_{ni}$ is the mixed error term; ν_{ni} represents a random variable; μ_{ni} indicates management inefficiency; the random error term $\nu \sim N(0, \sigma_\nu^2)$ represents the influence of random interference factors on the input slack variable; μ represents the impact of management factors on the input slack variable: if μ obeys the normal distribution truncated at zero, the range equals $\mu \sim N^+(0, \sigma_\mu^2)$. All decision-making units can be adjusted to the same external environment. The adjustment formula is as follows:

$$X_{ni}^{A} = X_{ni} + \left[\max\left(f\left(Z_i; \hat{\beta}_n^{u}\right)\right) - f\left(Z_i; \hat{\beta}_n^{u}\right)\right] + \left[\max(\nu_{ni}) - \nu_{ni}\right]$$
$$i = 1, 2, L, I;\ n = 1, 2, L, N \quad (3)$$

In **Eq. 3**, X_{ni}^A and X_{ni} are defined as the adjusted investment and investment before adjustment, respectively; $\max(f(z_i; \widehat{\beta_n^{u}})) - f(z_i; \widehat{\beta_n^{u}})$ presents the adjustment the external environmental; and $\max(\nu_{ni}) - \nu_{ni}$ places all decision-making units under the same environmental level.

The third stage is the adjusted input-output variable DEA efficiency analysis. Using the adjusted input variables to calculate the efficiency value of each decision-making unit again, which has eliminated the influence of environmental factors and random factors, ensures the values are relatively accurate.

We analyzed the human capital factors of effects on GTFP efficiency through the Tobit regression. First, considering the total effect of human capital (Edu), fiscal education spending (Edu Fiscal), and regional innovation (patent) on GTFP, the regression model is as follows:

TABLE 1 | Description of variables.

Variable type	Variable name	Symbol	Variable description	Unit	Mean	Standard deviation
Input variable	Energy Consumption	EC	Total energy consumption	10,000 tons of standard coal	10,779.18	7,702.263
	Material Capital	MC	Physical capital stock	(people/10,000 yuan) (price in 2000)	17.448	58.88
	Labor input	Lab	Number of employed persons	Ten thousand people	2,498.416	1,670.947
Output system	Economic development	Eco	per capita *GDP*	yuan (Price in 2000)	49.382	35.178
	Carbon Emission	Co_2	Carbon dioxide emissions	Ten thousand tons	27,513.56	21,524.37
Environmental factor	Industrial development	Ind	The proportion of the secondary industry in GDP	%	46.437	7.778
	R&D investment level	Rd	Full-time equivalent of R&D personnel	Person year	73,569.85	90,715.93

$$GTFP_{it} = \beta_0 + \beta_1 X_{it} + \beta_3 Controls + \varepsilon_{it} \quad (4)$$

We further considered the interaction effect of human capital accumulation level, fiscal education spending, foreign direct investment (FDI), marketization degree on GTFP, the interaction effect of the level of regional innovation, and the level of intellectual property protection on GTFP. The interaction model is as follows:

$$GTFP_{it} = \beta_0 + \beta_1 X_{it} + \beta_2 Z_{it} + \beta_3 Z_{it} \times X_{it} + \beta_4 Controls + \varepsilon_{it} \quad (5)$$

In **Eqs 4**, **5**. $GTFP_{it}$ represents the efficiency with GTFP of the region "*i*" in year *t*;X_{it} defines the three explanatory variables in the article, including human capital accumulation, education fiscal expenditure, and the level of regional innovation. In addition, Z represents three variables: the degree of openness, marketization, and the production of intellectual property rights (IPR); ε_{it} is a random error term.

The function with the interaction term of X and Z is to investigate hypothesis two. Besides, to reduce the endogenous problems caused by missing variables, we still control a series of variables that have been proven to have a significant impact on GTFP.

Variables

This paper investigates the effects of human capital on GTFP. The variables include two sectors: the three-stage DEA variables and the mediation effects model through Tobit regression.

Variables of the Three-Stage DEA

This section analyzes GTFP and its decomposition. Therefore, the explained variable is GTFP, measured by three-stage DEA in *Analysis of the Dynamic GTFP*. In this paper, the description of variables is in **Table 1**, and the input and output indicators are as follows.

Input indicators: 1) the energy consumption inputs reflect the efficiency of green products, which is represented by the amount of energy consumption. 2) The material capital input highlights the level of capital input in terms of the progress of production, which is usually represented by the increasing investment in fixed assets. 3) The labor input reflects the number of employees, which is represented by the amount of employment at the enterprise.

Output indicators are as follows: 1) the desired output indicator is GDP, representing Per Capital GDP in each province; and 2) the carbon emission is an undesired output indicator that highlights green production. At the same time, at the second stage, we need to eliminate those facts that affect the efficiency of GTFP and cannot be changed in a short time, including two key factors for a full-time equivalent (FTE) of R&D and full-time equivalent (FTE) of R&D personnel.

The large gap between provinces in China, particularly the economic gaps, would affect the GTFP. We selected the secondary industry's proportion of GDP and the full-time equivalent (FTE) of R&D as environmental factors.

Variables of Mediation Effects Model

This study adopts Tobit regression to analyze the interaction effects of heterogeneous human capital on GTFP efficiency. Traditional regression models may face bias issues between variables. This study uses the Tobit model for the empirical analysis to eliminate the errors caused by the range from 0 to 1 for GTFP variables, effectively solving explanatory variables' bias. The variables used in this study are outlined in **Table 2**.

Core explanation variables include the following. 1) Human capital is represented by the average education years in labor. 2) *Fiscal education expenditure* is defined as the ratio of expenditure on science and education to fiscal expenditure; it also emphasizes government attention. 3) *Regional innovation* is represented by the number of domestic patent applications.

Explained variable: This section analyzes the effects of human capital on GTFP efficiency. Thus, the explained variable is GTFP, and the evaluation value of efficiency is to eliminate the environmental interference factors.

Control variables are as follows. 1) Economic development level (per capita GDP): this directly reflects the economic level of each province. A higher level of economic development in the region means that technology agglomeration improves the GTFP. 2) Industrialization level (IGDP): from the perspective of the entire industry chain, the green technology level can help improve the GTFP. The industrialization level is defined by the percentage of industrial production to the regional GDP. 3) Infrastructure construction level (Road): this impacts green industrialization and improves the efficiency of an economy. The infrastructure construction level is represented by

TABLE 2 | The Descriptive variables of tobit Model.

Types of	Variable name	Symbol	Variable description	Unit	Mean	Standard deviation
Explained variable	Circular economy development efficiency	GTFP	Efficiency after removing environmental interference factors	—	0.89	0.15
	Human capital level	Edu	Average years of education in labor	year	10.497	1.263
Explanatory variables	education fiscal spending	EduF	Ratio of expenditure on science and education to fiscal expenditure	%	17.645	29.792
	Regional innovation	Patent	Number of domestic patent applications	Pieces/10,000 people	4.233	7.175
	The level of economic development	PGDP	GDP per capita	Yuan/person	49.382	35.178
Control variable	Industrialization level	IGDP	The added value of the secondary industry accounts for the proportion of regional GDP	%	46.437	7.778
	Infrastructure construction level	Road	Urban road area per capital	Square meter	12.069	4.336
	Urbanization rate	Urban	Proportion of urban population in total population	%	48.175	15.307
	Social investment level	SI	Total investment in fixed assets of the whole society	Ten thousand yuan	116,286.7	139,419.6
	Foreign investment level	FDI	Total foreign investment/GDP	%	0.434	0.542
Moderator	Marketization level	Market	Marketization index	—	6.642	2.083
	Protection of Intellectual property	TMR	The ratio of technology market transaction to regional GDP	%	1.008	2.091

Note: The fiscal education spending was calculated using the (three science and technology expenses + education expenses) before 2006, while the fiscal education spending has been calculated using (education + science and technology expenditure) after 2006; the marketization index from China's Marketization Index Report by Provinces.

the urban road area per capita. 4) Urbanization level: an urbanization process brings about higher spillover effects on technology and human capital. We adopt a proportion of the urban population in the total population to represent the urbanization level. 5) Social investment in fixed assets: total fixed-asset investment is a prerequisite for the development of regional GTFP. The investment in different regions determines the willingness of enterprises to update green technologies. Social fixed assets investment is expressed as the total investment in fixed assets of the whole society.

Mediating variables are as follows: 1) foreign investment, foreign direct investment (FDI) through human capital, competition effects, and knowledge spillover effects to improve GTFP. We measure FDI through the index of annual foreign investment utilized in GDP. 2) The higher the marketization level, the stronger the willingness to introduce green advancement technology and new talent. Considering the availability of data, we measure the variable of marketization index from the Report on Marketization Index of China. 3) Intellectual Property Rights (IPR) Protection: the IPR protection level is the fundamental driving force for green technology innovation, conducive to stimulating enterprise enthusiasm for innovation and constructing an excellent innovation atmosphere. The measurement index is the ratio of technology transactions in the regional GDP. In addition, we expect these variables may influence the efficiency of GTFP.

Data Source

Considering available data, we excluded data from Tibet, Hong Kong, Macau, and Taiwan. The panel datasets were constructed by 30 provinces from 2001 to 2018. The primary data were calculated from the China Urban Statistical Yearbook and China's Energy Statistical Yearbook. The energy consumption data from the statistical Yearbooks of provinces and the marketization index measured from the Report with China's Marketization Index by Fang (2019) are worth mentioning. The index of Carbon dioxide emissions was collected from the eight types of energy consumption, including diesel consumption, coke consumption, coal consumption, kerosene consumption, gasoline consumption, fuel oil consumption, crude oil consumption, and natural gas consumption. Then evaluation the coefficient of energy conversion to the carbon. The inter-provincial material capital stock is calculated based on the relevant data and methods of Zhang Jun (2004), and the measuring equation is $K_{it} = K_{it-1}(1 - \delta_{it}) + I_{it}$.

RESULTS

The following sections present the main analysis of GTFP efficiency and the influencing factors in the various provinces. Fully dynamic and static models are used to analyze the GTFP; the results are discussed below.

Analysis of the Dynamic GTFP

Materials, capital, labor, and energy consumption are taken as input variables; the province's GDPs are taken as the expected output, and CO_2 is taken as the undesired outputs. GTFP efficiency in 30 provinces is calculated using three-stage DEA. This is because we can distinguish between the different spatial and time trends. According to the division method of Chinese administrative regions, the provinces are divided into Northeastern, Eastern, Central, and Western China. The Northeastern provinces include Jilin, Liaoning, and Heilongjiang. The Eastern provinces include Hebei, Beijing, Tianjin, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian,

TABLE 3 | Green total productivity of province from 2001 to 2018.

Province	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Beijing	0.868	0.872	0.925	0.887	0.887	0.935	0.947	0.928	0.987	0.995	1	1	1	1	1	1	1	1
Tianjin	0.878	0.901	0.846	0.857	0.857	0.834	0.896	0.915	0.893	0.896	0.947	0.958	0.929	0.920	0.904	0.887	0.877	0.875
Hebei	1	0.880	0.841	0.844	0.844	0.875	0.861	1	1	1	1	1	1	1	0.939	0.994	0.947	0.909
Shanxi	0.990	0.994	1	1	1	1	1	1	0.993	0.992	0.998	1	0.998	0.994	0.986	0.995	0.989	0.971
Inner Mongolia	0.908	0.904	0.861	0.847	0.847	0.901	1	0.921	1	1	1	1	1	1	1	1	1	1
Liaoning	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jilin	0.936	0.889	0.797	0.808	0.808	0.811	0.877	0.873	0.913	0.919	0.931	0.959	0.938	0.875	0.899	0.846	0.835	0.768
Heilongjiang	0.877	0.948	0.898	0.912	0.912	0.901	0.955	0.961	0.984	0.996	1	1	1	0.989	0.997	0.984	0.915	0.880
Shanghai	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jiangsu	1	0.993	0.998	1	1	1	1	1	1	1	0.939	0.96	0.966	1	1	1	1	1
Zhejiang	1	0.978	0.983	0.992	0.992	1	1	1	1	1	1	1	0.999	1	1	1	1	1
Anhui	0.888	0.937	0.906	0.921	0.921	0.901	0.960	0.974	0.989	0.997	0.997	0.997	0.994	0.988	1	0.991	0.942	0.948
Fujian	0.822	1	0.941	0.825	0.825	0.847	0.881	0.871	0.885	0.881	0.913	0.908	0.909	0.880	0.935	0.931	0.919	0.916
Jiangxi	0.591	0.836	0.740	0.730	0.730	0.743	0.809	0.809	0.807	0.794	0.838	0.823	0.824	0.780	0.780	0.785	0.799	1
Shandong	1	0.997	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.982
Henan	1	0.973	0.951	0.981	0.981	0.992	1	1	1	1	1	1	0.997	1	1	1	1	1
Hubei	0.904	0.948	0.916	0.943	0.943	0.926	0.971	0.977	0.991	0.998	1	1	1	0.998	1	0.997	0.987	0.982
Hunan	0.774	0.889	0.859	0.83	0.83	0.857	0.898	0.936	0.920	0.933	0.935	0.942	0.934	0.906	0.918	0.928	0.915	0.951
Guangdong	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Guangxi	0.838	0.871	0.820	0.837	0.837	0.851	0.933	0.938	0.939	0.907	0.953	0.993	1	0.964	0.995	0.974	0.947	0.882
Hainan	0.598	0.563	0.570	0.527	0.527	0.501	0.806	1	1	1	1	1	1	0.850	1	1	0.960	0.687
Chongqing	0.511	0.609	0.613	0.589	0.589	0.569	0.611	0.622	0.619	0.621	0.625	0.639	0.636	0.654	0.699	0.696	0.692	0.731
Sichuan	1	0.814	0.851	0.86	0.860	0.820	0.862	0.925	0.913	0.942	0.907	0.871	0.862	0.875	0.920	0.875	0.838	0.961
Guizhou	1	0.830	0.752	0.800	0.800	0.718	0.845	0.849	0.891	0.921	0.904	0.933	0.961	0.896	0.853	0.833	0.794	0.666
Yunnan	0.615	0.716	0.747	0.804	0.804	0.778	0.841	0.825	0.828	0.843	0.816	0.778	0.764	0.765	0.747	0.700	0.680	0.671
Shaanxi	1	0.793	0.759	0.853	0.853	0.799	0.908	1	0.971	1	1	1	1	1	1	1	0.936	1
Gansu	0.847	0.882	0.812	0.83	0.830	0.776	0.891	0.940	0.973	0.977	0.967	0.985	0.981	0.913	0.919	0.923	0.837	0.719
Qinghai	0.285	0.371	0.336	0.319	0.319	0.302	0.370	0.365	0.401	0.406	0.409	0.405	0.439	0.387	0.375	0.359	0.368	0.349
Ningxia	0.398	0.740	0.623	0.543	0.543	0.610	0.583	0.571	0.657	0.704	0.862	0.907	0.980	0.872	0.901	0.912	0.826	0.601
Xinjiang	0.871	0.858	0.745	0.764	0.764	0.780	0.824	0.838	0.869	0.948	0.989	1	1	1	1	1	1	0.859
Nationwide	0.847	0.866	0.836	0.837	0.837	0.834	0.884	0.901	0.914	0.922	0.931	0.935	0.937	0.917	0.926	0.92	0.900	0.877
East	0.917	0.918	0.91	0.893	0.893	0.899	0.939	0.971	0.977	0.977	0.980	0.983	0.980	0.965	0.978	0.981	0.970	0.937
Central	0.858	0.930	0.895	0.901	0.901	0.903	0.940	0.949	0.950	0.952	0.961	0.960	0.958	0.944	0.947	0.949	0.939	0.975
West	0.752	0.763	0.720	0.731	0.731	0.719	0.788	0.799	0.824	0.843	0.857	0.865	0.875	0.848	0.855	0.843	0.811	0.767
Northeast	0.938	0.946	0.898	0.907	0.907	0.904	0.944	0.945	0.966	0.972	0.977	0.986	0.979	0.955	0.965	0.943	0.917	0.883

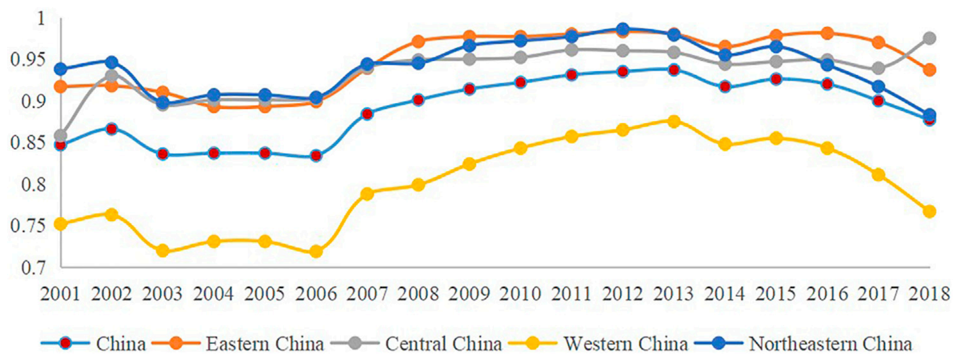

FIGURE 2 | Gtfp variation diagram at four sections.

Guangdong, and Hainan. Central provinces include Henan, Hubei, Hunan, Anhui, Jiangxi, and Shanxi. The Western provinces include Chongqing, Sichuan, Guizhou, Yunnan, Guangxi, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang, and Inner Mongolia.

As shown in **Table 3**, the changing trend of GTFP at the province level is significant. The results indicate that the general GTFP in China was 0.847 in 2001 and 0.877 in 2018. This reveals a wave-like upward trend from 2001 to 2018. The average value of GTFP has seen a continuous and rapid increase from 2006 to 2008. In 2008, the average value of GTFP efficiency was more than 0.9, an increase of about 8%. The possible reason is the Chinese government has focused on promoting green, circular, and low-carbon development to advocate the concept of the "Green Olympics" around the world. The government has proposed the policy of "Beautiful China." In 2013, GTFP reached its peak value of 0.937. However, it did not reach the production Frontier and began to decline after 2014. It shows that resource mismatch issues exist in the process of "Input-output" GTFP in China. In other words, the input resources have converted to output products inefficiently, and the scale of resource input has not yet reached the optimal production scale. As can be seen from **Table 3**, from 2001 to 2018, the values of GTFP remained steadily in the production Frontier only in Beijing, Shanghai, Tianjin, Zhejiang, Guangxi, Hainan, and Qinghai. It indicates that these provinces can effectively transform input factors into output factors and match "Input-output." We also find that only two provinces, Jiangsu and Fujian, have been at the forefront of GTFP for a long time. However, other provinces (e.g., Chongqing, Hunan, Hubei, and Xinjiang) are at the non-Frontier, which shows that most provinces in China still have to improve GTFP efficiency.

The advantage of three-stage DEA is the further decomposition of GTFP. To analyze the difference among provinces, we compose provinces into four regions. **Figure 2** shows the changes in GTFP in four sections from 2001 to 2018. From 2008 to 2017, GTFP shows an upward trend. In addition, the changing trend of GTFP in the Eastern region is significantly significant. The agglomeration of high-tech enterprises, human capital, and government finances in the Eastern region has accelerated efforts to upgrade and optimize its industrial structure. Furthermore, the marketization of the Eastern region is lower than other regions. It means that the value of GTFP can be improved by promoting the enthusiasm of economic entities and the rational allocation of factor resources.

Table 4; **Figure 3** show the GTFP values of 30 provinces in China. Furthermore, they analyze the growth model of GTFP. This paper is based on the average values of the province's GTFP from 2001 to 2018 to divide provinces into four types: low effective growth, weak effective growth, adequate solid growth, and highly effective growth. As shown in **Table 4**, the GTFP values with influential growth provinces are more significant than 0.916. Regarding weak and low effective growth, the values with weak and low influential growth model provinces are lower than 0.810.

From **Figure 3**, it also can be seen the spatial distribution difference of the growth model of GTFP from 2001 to 2018. Those provinces with high influential growth models are concentrated in eastern regions, such as Beijing, Shanghai, and Jiangsu. Occasionally, Sichuan and Hunan, being located in the central and western regions, and Guizhou, Gansu, Xinjiang, Guangxi, and Jilin, being located in the Northeast, have belonged to the solid and effective growth model. Weak and low practical growth models are for the majority concentrated in western regions except for Hainan. It suggests that improving the value of GTFP can enhance the utilization efficiency of resources in the western region and achieve the convergence of the difference with the highly effective growth area.

Analysis of GTFP and Its Static Decomposing

To analyze the efficiency of GTFP scientifically, this paper excludes environmental factors and random noise by a three-stage DEA model to obtain the GTFP static decomposing results, which include pure technology efficiency, scale technology efficiency, and return to scale. The initial DEA model results, without considering the impact of environmental factors and random noise, are shown in **Table 5**. From the Frontier's technological index in 30 provinces, the average GTFP efficiency is 0.79, the average technical efficiency is 0.889, and the average scale efficiency is 0.891. Specifically, the provinces include Beijing, Guangdong, Jiangxi, Inner Mongolia, Shaanxi,

TABLE 4 | The growth model of GTFP efficiency.

Growth type	Low effective growth (E ≤ 0.629)	Weak effective growth (0.629 ≤ E ≤ 0.810)	Strong effective growth (0.810 ≤ E ≤ 0.916)	High effective growth (E ≥ 0.916)
Provinces	Chongqing, Qinghai	Yunnan, Ningxia, Jiangxi, Hainan	Gansu, Xinjiang, Sichuan, Jilin, Guizhou, Hunan, Guangxi	Beijing, Shanxi, Inner Mongolia, Shanghai, Fujian, Jiangsu, Shandong, Henan, Liaoning, Hebei, Hubei, Anhui, Shaanxi, Guangdong, Heilongjiang, Tianjin, Zhejiang

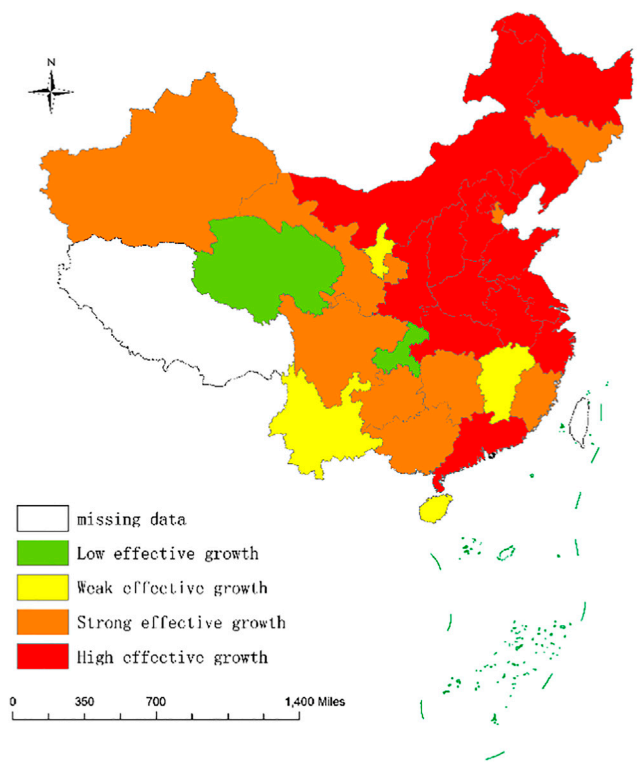

FIGURE 3 | Spatial distribution diagram of GTFP.

and Shanghai, which have reached the forefront of production, and their scale efficiencies are 1. In terms of provinces in the eastern region, except for Beijing, Guangdong, and Shanghai, which reach the forefront of production, the values of other provinces are all lower than 0.9; Hebei's, in particular, is lower than 0.78. Overall, the eastern region's average efficiency is only 0.839, the average technical efficiency is 0.881, and the average scale efficiency is 0.857.

From the GTFP efficiency results of provinces in the central region, only Jiangxi is at the production Frontier. Generally, the average efficiency of these provinces is 0.757, average technical efficiency is 0.776, and average scale efficiency is 0.975. From the western region results, two provinces, Inner Mongolia and Shaanxi have reached the production Frontier. The average efficiency value of provinces in the western region is 0.789, the average value of technical efficiency is 0.980, and the average value of scale efficiency is 0.876. Specifically, provinces in the northeast region are not at the forefront of production. For example, the Northeast region's average efficiency value is 0.706, the average value of technical efficiency is 0.807, and the average scale efficiency is 0.89.

The first-stage efficiency results indicate that the efficiency of GTFP is ineffective, and the scale efficiency is generally lower than the pure technical efficiency. On the other hand, the issues of insufficient resource utilization in GTFP remain in China. The eastern and western regions have redundant input variables, and the efficiency of scale inhibits the improvement of the efficiency of GTFP. In contrast, the efficiency of scale in the central and northeastern regions is generally higher than the pure technical efficiency. The reason may be the different levels of government governance and technical restrictions. To exclude the effects factors of socio-economic, regional development, and random interference on the GTFP, this paper analyzes the GTFP by second SFA regression.

The Second Stage of SFA Regression

Based on the three input indicators in the first stage, the explained variables and the independent variables are the proportion of the secondary industry in GDP. The full-time equivalent of R&D personnel is used to establish an SFA regression model. Then, we analyze the GTFP through the Frontier4.1 software. **Table 6** shows the SFA regression results, and it shows that the development of the secondary industry has a significant positive impact on the slack variables of energy consumption (3.37E + 01), material capital input (6.34E–02), and labor input (2.07E + 01).

Note that the likelihood of slack variables of energy consumption, material capital input, and labor input of −2.66E + 02, −6.99E + 01, and −2.39E + 02 indicates the environmental factors and random interference factors significantly affect the efficiency of GTFP. The R&D investment positively affects the slack variable of energy input and labor input of 1.09E–03 and 7.01E–04. However, the R&D investment hurts the slack variable of material input of −3.12E–06.

Although the government has made great efforts to change the economic development model by regulating high pollution and supporting green enterprises, however, under the GDP assessment system, the waste phenomenon during the secondary industry's development process still exists. Considering the diversity of geography in China, the transfer of polluting industries from developed areas to inland provinces is increasingly common, and this carries on industrial transfer without adequate supervision. Therefore, the regions with more

TABLE 5 | GTFP and its breakdown over provinces in 2018.

Provinces	TE	PTE	SE	VRS	Provinces	TE	PTE	SE	VRS
Beijing	1	1	1	—	Henan	0.686	0.703	0.976	Drs
Tianjin	0.926	1	0.926	irs	Hubei	0.635	0.645	0.985	Irs
Hebei	0.780	0.974	0.800	drs	Hunan	0.762	0.796	0.958	Irs
Shanxi	0.717	0.732	0.980	irs	Guangdong	1	1	1	—
Inner Mongolia	1	1	1	-	Guangxi	0.611	0.678	0.901	Irs
Liaoning	0.626	0.636	0.985	drs	Hainan	0.788	1	0.788	Irs
Jilin	0.784	1	0.784	irs	Chongqing	0.805	1	0.805	irs
Heilongjiang	0.707	0.784	0.901	irs	Sichuan	0.779	0.801	0.972	irs
Shanghai	1	1	1	-	Guizhou	0.486	0.758	0.642	irs
Jiangsu	0.998	1	0.998	drs	Yunnan	0.538	0.799	0.673	irs
Zhejiang	0.829	0.835	0.992	drs	Shaanxi	1	1	1	—
Anhui	0.744	0.781	0.952	irs	Gansu	0.538	0.746	0.721	irs
Fujian	0.930	1	0.930	irs	Qinghai	0.427	1	0.427	irs
Jiangxi	1	1	1	—	Ningxia	0.790	1	0.790	irs
Shandong	0.925	1	0.925	drs	Xinjiang	0.921	1	0.921	irs

Note:1) TE = PTE×SE. 2) crs, irs, and drs represent constant returns to scale, increase return to scale, and diminishing return to scale, respectively.

TABLE 6 | SFA regression.

Variable	Energy input slack variable	Material input slack variable	Labor input slack variable
Constant term	−2.14E + 03***	−2.88E + 00***	−1.32E + 03***
The proportion of the secondary industry in GDP	3.37E + 01***	6.34E−02*	2.07E + 01***
R	1.09E−03***	−3.12E−06***	7.01E−04***
Sigma	1.37E + 07***	3.37E + 01***	2.22E + 06***
Gamma	1.00E + 00***	1.00E + 00***	1.00E + 00***
Likelihood	−2.66E + 02	−6.99E + 01	−2.39E + 02
LR	1.78E + 01***	2.30E + 01***	1.75E + 01***

*Note: *p < 0.10, **p < 0.05, ***p < 0.01.*

cluster industries and greater innovation systems will emphasize R&D investments and innovation more. It indicated that sustainable economic systems have a development tendency that causes the decline of material consumption and waste in economic development and strengthens intensive development by relying on human capital and innovation capital.

The above means it can reduce and achieve significant development. The input of R&D investment has not yet improved the input structure of labor and energy in the economic development system. The possible explanation is that excessive concentration of R&D investment and personnel leads to the internal waste of talent in these regions. While R&D investment also depends on industrial agglomeration, energy consumption will be higher in regions where many industries are concentrated.

TABLE 7 | The adjustment range of first and third stage.

	TE (%)	PTE (%)	SE
China	25.083	23.967	−0.824%
Eastern China	10.855	12.494	−1.586%
Central China	28.785	28.838	0.017%
Western China	3.505	2.168	1.295%
Northeastern China	5.102	11.297	−5.332%

Adjustment Results of DEA Model

The adjusted results of GTFP efficiency in 30 provinces in 2018 are shown in **Table 7**. Overall, after the adjustment, the average efficiency increased by 25%, and the average pure technical efficiency increased by 23%. However, it is interesting to observe that the scale efficiency fell by 0.82%. **Table 7** also shows the stripping away of environmental and random factors, where provinces in the central region increased by 28% in terms of the GTFP efficiency. The GTFP efficiency of eastern, northeast, and western provinces increases by 10, 5, and 3%, respectively.

It is well known that the environment is essential for GTFP in different regions, and the role of incentives for development efficiency is different. Nevertheless, the lower scale efficiency still causes the lower value of the adjusted GTFP. After the adjustment, each region's pure technical efficiency has increased significantly than the adjustment scale efficiency. Hence, after excluding the external environment and random error, the GTFP efficiency is still low. The main reason is the constraints of the scale efficiency.

Figure 4 shows the pre-and post-contrast evaluation for the GTFP. After the adjustment, the scale efficiency of the eastern and northeastern regions has declined. It means that there is potential for improving the scale efficiency of GTFP by improving the external environment. After the adjustment, the advantage is obviously on the provinces' scale efficiency in the central and western regions compared with other regions. Therefore, it is necessary to support

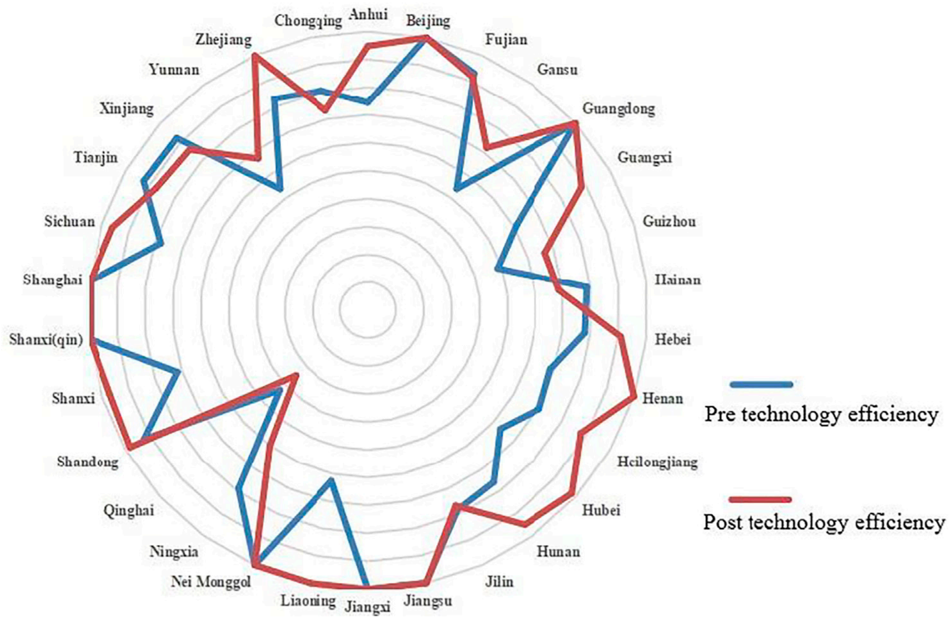

FIGURE 4 | Pre–post technology efficiency -contrast evaluation for the GTFP efficiency.

TABLE 8 | Unit root testing.

Variable	IPS	Fisher
Lngtfp	−10.1477***	12.2025***
Lnedu	−4.0369***	18.8831***
Lnte	−4.3017***	14.8162***
Lnpatent	−3.8855***	17.0481***
Lnrjgdp	−3.9212***	17.0313***
Lnseid	−4.3396***	16.9973***
Lnroad	−3.8187***	16.1646***
Lnurban	−3.8003***	16.5466***
Lninv	−3.9085***	16.8116***
Lnfdi	−4.1858***	14.9862***
Lnmarket	−4.0315***	16.0552***
Lntmr	−1.8761***	8.4020***

Note: *p < 0.10, **p < 0.05, ***p < 0.01.

the expansion of investment scale in those provinces, mainly focus on improving overall efficiency and technical efficiency. In terms of provinces in eastern and northeastern regions, it is necessary to avoid resource redundancy and waste caused by excessive investment.

Panel Unit Root Test and Cointegration Test

To avoid false regression and pseudo-regression problems, it is first necessary to perform a unit root test on panel data to ensure the validity of model estimation results. We do the root test methods through IPS (Im-Pesaran-Skin Test) and FISHER tests. If the null hypothesis that there is a unit root in these two tests is rejected, it means that the panel sequence is stationary. **Table 8** shows the unit root test results of each variable. It can be concluded that the original level sequence is not stable in **Table 8**.

Therefore, the cointegration testing can be further performed. The null hypothesis tested is that the variables do not have a cointegration relationship. **Table 9** shows the cointegration test results of all models. It can be seen that in all models, each indicator rejects the null hypothesis of no cointegration relationship at a significance level of 1%. It can be considered that there is a long-term stable equilibrium relationship between the variables, and the result of further regression of the model is credible.

Analysis on the Effects of Human Capital on GTFP Efficiency

The value of GTFP is a restricted dependent variable. The paper further analyzes the mechanical effects of human capital on GTFP through the Tobit regression. **Table 10** represents the results after control variables of investment rate, social investment, and industrial development. As seen in **Table 10**, models (1), (4), and (7) explore the effects of three human capital types, including human capital accumulation, fiscal education expenditure, and regional innovation, respectively, on GTFP efficiency. We find that the effects of human capital accumulation and education fiscal expenditure all positively affect the GTFP of 0.0231 and 0.484, respectively.

On the other hand, financial science and education investment play an essential role in achieving the convergence of the regional economic development level gap. Considering that China's underdeveloped regions depend on infrastructure investment, the expansion of financial investment in education will cause "crowding out" effects, reducing the waste of resources by squeezing out the infrastructure construction of low repeat levels. However, the effects of the negative coefficients of regional innovation are −0.0439.

TABLE 9 | Panel cointegration testing.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Modified Dickey–Fuller t	−4.01***	−3.97***	−4.1***	−4***	−3.87***	−3.93***	−4.01***	−3.95***	−4.1***	−4.05***
Dickey–Fuller t	−10.08***	−9.81***	−9.94***	−10.05***	−9.6***	−9.98***	−9.94***	−9.65***	−10.11***	−9.84***
Augmented Dickey–Fuller t	−4.19***	−4.29***	−4.23***	−4.17***	−4.42***	−3.89***	−4.44***	−4.55***	−4.32***	−3.78***
Unadjusted modified Dickey–Fuller	−17.67***	−17.56***	−17.48***	−17.54***	−17.16***	−17.25***	−17.52***	−17.41***	−17.67***	−16***
Unadjusted Dickey–Fuller t	−15.88***	−15.58***	−15.56***	−15.81***	−15.27***	−15.67***	−15.66***	−15.35***	−15.83***	−14.86***

Note: *p < 0.10, **p < 0.05, ***p < 0.01.

Models (2), (5), and (8) have added the degree of openness, the human capital accumulation, and the fiscal education expenditure, respectively, to analyze the heterogeneous effects of openness on GTFP further. They are observing the results of models (2), (5), and (8), the cross-term coefficients between levels of openness with human capital accumulation, fiscal education expenditure, and innovation level of 0.0408, 1.919, and 0.000825, respectively.

Models (3), (6), and (9) have added the cross-term between marketization and human capital accumulation, fiscal education expenditure, and innovation. Analyze the heterogeneous effects of marketization on GTFP. The cross-term coefficients between marketization levels with human capital accumulation, fiscal education expenditure, and innovation level of −0.00618, −0.236, and −0.00162, respectively.

Model (10) explores the heterogeneous effects of intellectual property protection on GTFP. This paper adds the cross-term of innovation and intellectual property protection. The cross-term coefficients between intellectual property protection and innovation are 0.00000879 it means intellectual property protection improves the adverse effects of innovations on GTFP. Hence, the government should address the policy of intellectual property protection in developing cities.

Robustness Test

This study uses the variable substitution method and data substitution method to perform the robust test. First, the variable substitution method uses a Two-way fixed OLS model. It adjusts the variables of CO2 emissions per GDP and COD emissions per GDP to measure the effects of human capital on GTFP efficiency. It can be seen from **Table 11** that human capital, financial technology, and fiscal education expenditure still have adverse effects on the energy consumption scale and pollution discharge (−14.45 and −55.78, respectively) and the positive effects of innovation on the energy consumption scale and pollution discharge (0.337). Secondly, the data substitution method removes extreme values; the robustness test shown in **Table 10**. From the robust results, we find that the coefficient of human capital, financial technology, and education expenditure on the GTFP is still significant, and the control variable's result did not significantly change. Overall, two robust tests further verify that the selection of variables is reasonable, and the model is robust.

Table 12 shows the trend efficiency results of Western region provinces. The GDFP shows a tendency to increase, while the Western area still has the lowest technology efficiency of the three regions (Eastern, Western, and Central areas) of China. It means that the level of advancement of its industrial structure and technological innovation capabilities are relatively weaker than other regions, which will inevitably affect its GTFP. In terms of Central regions, the changing trend of GTFP efficiency has the same as the national average, which shows an upward trend in volatility. The empirical results demonstrate that the values ranged from 0.858 in 2001 and peaked at 0.975 in 2018. With abundant natural resources, convenient traffic conditions, and water resources, Hubei and Jiangxi in the Central region have potential development in terms of GTFP. Implementing a "promote Central region raising strategy" improves governments' enthusiasm for industrial transformation and upgrading, which has provided favorable conditions for developing a green economy. As seen from the trend for the Northeast region, the value of GTFP remains at a relatively high level. With the implementation of the Northeast revitalization strategy policy and the dilemma of surviving the economy, local governments experiencing a slump have sought to transform the economic development model by constructing the first chemical industry circular economy demonstration park.

DISCUSSION

This study analyzed the heterogeneous effects of human capital on GTFP efficiency in China. Therefore, we revised the input-output factors of GTFP and excluded external factors and stochastic noise through the three-stage DEA and Tobit regression model.

As expected, the effects of human capital accumulation and fiscal education expenditure all positively affect GTFP. Financial science and education investment play essential roles in achieving the convergence of the regional economic development level gap. From the micro perspective, the growth of human capital accumulation means that high-quality labor has a greater ability to allocate resources and absorb advanced technology, resulting in a mature "Labor reserve." In other words, an increase in the high-quality population in "Labor cisterns" results in a greater probability that companies can hire high-quality workers at a lower cost and achieve growth of efficiency with less labor investment. From the macro perspective, the government's investment in education is used as "Leverage," which means it can also increase education investment in micro entities, such as enterprises and families, directly affecting labor quality. However, the financial investment in education will cause crowding out

TABLE 10 | Tobit regression.

	(1)	(2)	(3)		(4)	(5)	(6)		(7)	(8)	(9)	(10)
Edu	0.0231**	0.0320***	0.00859	te	0.484*	0.611**	0.511*	patent	−0.00439***	−0.00489***	0.00283	−0.00607***
	(2.24)	(2.95)	(0.71)		(1.86)	(2.40)	(1.96)		(−3.30)	(−3.24)	(0.91)	(−4.30)
Fdi		0.0497***		fdi		0.0447***		fdi		0.0364**		
		(3.46)				(3.71)				(2.42)		
Edu*fdi		0.0408**		Te*fdi		1.919***		market			0.00195	
		(2.07)				(3.28)					(0.33)	
Market			0.000900	market			0.000879	Paten*fdi		0.000825		
			(0.14)				(0.15)			(0.29)		
Edu*market			−0.00681***	Te*market			−0.236**	Patent*market			−0.00162***	
			(−2.61)				(−2.48)				(−2.63)	
								tmr				−0.0000781
												(−1.35)
								Patent*tmr				0.00000879**
												(2.10)
Control variables	Yes	Yes	Yes	Control variables	Yes	Yes	Yes	Control variables	Yes	Yes	Yes	Yes
_cons	0.436***	0.315***	0.632***	_cons	0.574***	0.526***	0.608***	_cons	0.698***	0.680***	0.709***	0.667***
	(4.02)	(2.70)	(4.48)		(8.46)	(7.74)	(8.86)		(11.66)	(11.32)	(11.60)	(10.95)
sigma_u	0.164***	0.166***	0.160***	sigma_u	0.162***	0.168***	0.155***	sigma_u	0.168***	0.168***	0.165***	0.166***
	(6.96)	(6.97)	(6.85)		(6.92)	(6.90)	(6.78)		(6.99)	(7.00)	(6.91)	(6.98)
sigma_e	0.0735***	0.0722***	0.0726***	sigma_e	0.0739***	0.0716***	0.0733***	sigma_e	0.0728***	0.0719***	0.0723***	0.0709***
	(23.86)	(23.82)	(23.85)		(23.88)	(23.87)	(23.86)		(23.86)	(23.84)	(23.89)	(23.31)
N	480	480	480	N	480	480	480	N	480	480	480	452

*Note: *p < 0.10, **p < 0.05, ***p < 0.01; Standard errors in parentheses.*

TABLE 11 | Robustness test (two–way fixed OLS model).

Variables	CO_2_GDP			COD_GDP		
edu	−0.228**			−14.45**		
	(−2.39)			(−2.28)		
te		−2.996			−55.78	
		(−1.32)			(−0.37)	
patent			0.0496***			0.337
			(4.45)			(0.45)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
_cons	5.638***	4.007***	2.804***	364.7***	242.2***	229.0***
	(5.87)	(7.48)	(6.16)	(5.71)	(6.79)	(7.42)
N	510	510	510	510	510	510

*Note: *p < 0.10, **p < 0.05, ***p < 0.01; Standard errors in parentheses.*

TABLE 12 | Robustness test (removal of extreme values).

Variables	GTFP	GTFP	GTFP
edu	0.0181*		
	(1.66)		
te		0.516*	
		(1.92)	
patent			−0.00925***
			(−4.16)
Control variables	Yes	Yes	Yes
_cons	0.486***	0.568***	0.706***
	(4.42)	(8.21)	(11.91)
sigma_u	0.165***	0.162***	0.169***
	(6.97)	(6.93)	(6.99)
sigma_e	0.0736***	0.0738***	0.0721***
	(23.84)	(23.89)	(23.87)
N	480	480	480

*Note: * p < 0.10, ** p < 0.05, *** p < 0.01; Standard errors in parentheses.*

effects in developing regions; the possible explanation is that China's regional development gap is significant. Underdeveloped regions lag behind developed regions in terms of innovation, lack of institutional environment, material capital accumulation, and insufficient infrastructure. It causes the erosion effect on innovation growth, leading to the inefficient allocation of resources, and distorting the effect of innovation on TFP.

In terms of marketization, growth will reduce the positive impact of human capital and fiscal education expenditure on GTFP. Since coastal areas have gotten rid of the influence of the planned economy, and enjoy more institutional dividends, it has caused geographic differences in the level of marketization between coastal and Western regions of China. Therefore, the marketization differences lead to the agglomeration effects on talents and capital elements in coastal areas. The loss of high-quality resources will remain in underdeveloped areas when the marketization does not reach the "threshold." It will lead to low efficiency of GTFP and a severe waste of resources in underdeveloped areas. Besides the growth of openness, the degree will increase the positive impact of high-quality labor and education fiscal expenditure on GTFP.

On the contrary, it will weaken the influence of innovation on GTFP. FDI "overflow" effects caused by human capital accumulation is one of the main channels to improve the quality of the regional labor force. Specifically, multinational companies with a perfect talent training system will be willing to export considerable skilled labor to the local market, enhancing the level of regional human capital. Especially for underdeveloped regions, the representative's medium-quality human capital can play a more critical role in the regional economy. They can achieve the model transformation to environment-friendly economic development by imitating advanced regions. Local enterprises can absorb advanced international technologies through cooperation with multinational enterprises from developed regions, followed by the cultivation of high quality, innovative talents, the imitating of advanced systems, and advanced concepts to realize the goals of technological catch-up. These all play an essential role in reducing the waste of resources.

This study has several attributes: First, we use three-stage DEA to estimate the GTFP by excluding external and stochastic noise. Second, compared with current literature, we accounted for the different spatial and temporal heterogeneity in China; we used province-level data from 2001 to 2018 to measure spatial and temporal heterogeneity in GTFP efficiency. Finally, we conducted an integrated analysis on the influences of human capital and policy evaluation on GTFP efficiency, which extends the current literature on GTFP. However, this study has some limitations. We interpreted our findings based on the GTFP efficiency of all industries in China and do not separate the efficiency among primary, secondary, and tertiary industries.

CONCLUSION

After excluding external factors and stochastic noise, this study examined the effects of human capital heterogeneity on GTFP and tests sustainable paths. Considering the spatial and temporal heterogeneity, panel data from 30 provinces from 2001 to 2018 in China were adopted. We then verified two hypotheses about the heterogeneous effects of human capital through three-stage DEA and Tobit regression. The three types of human capital variables include human capital accumulation (Edu), education fiscal (Edu Fiscal), and regional innovation (patent). The main findings were as follows:

1) The average value of GTFP efficiency can be viewed as an inverted U-shape and shows significant geographic differences across China. The average efficiency of GTFP in Eastern regions (0.916) is higher than in other areas. The average efficiency of GTFP in the Western region (0.810) is significantly lower than in other areas. In terms of the GTFP growth model, except the Western provinces, including Guangxi, Guizhou, Gansu, Xijiang, and Sichuan, other provinces belong to a low-efficiency growth model.
2) The static decomposing for GTFP efficiency in 2018 shows that the average overall efficiency of GTFP rose by 25% in China, and the average pure technical efficiency rose by 23%. However, the scale efficiency decreased by 0.82%. Therefore, future research must take the geographic diversity of GTFP efficiency into consideration.
3) Analyzing the heterogeneous human capital effects of GTFP efficiency, human capital accumulation, and fiscal education spending shows that they are found to positively affect the GTFP efficiency. On the contrary, lack of an environmental institution, the inadequacy of resource capital, and insufficient infrastructure would lead to the erosion effect for innovation, which negatively affects GTFP efficiency.
4) FDI has positive effects on GTFP efficiency. Specifically, FDI will increase the positive effects of human capital accumulation, fiscal education spending, and innovation on GTFP efficiency. However, under the diverse geography in China, the growth of marketization will weaken the positive impact of human capital and education on GTFP efficiency.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Materials, further inquiries can be directed to the corresponding authors.

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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Intensive Agriculture as Climate Change Adaptation? Economic and Environmental Tradeoffs in Securing Rural Livelihoods in Tanzanian River Basins

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Tanzania is one of the East African countries most vulnerable to climate change impacts. Droughts and floods in 2015–16 had devastating effects on food production, crop failures and livestock deaths reaching record levels. One of the underlying projects of the Tanzanian government to mitigate these impacts is the Southern Agricultural Growth Corridors of Tanzania (SAGCOT), an area spanning the country's largest river basin, the Rufiji, where it collaborates with national and transnational companies to intensify irrigated crop production. Irrigation, drought-tolerant seeds, and employment are three of the key government-advised strategies to help smallholders increase crop yield, adapt to climate change, and alleviate poverty through the corridor. However, little research is available on whether these goals have been achieved. This paper aims to contribute to the literature by assessing harvest and income levels following the 2015–16 drought. Through fieldwork conducted in 2016–17 in Usangu, a key paddy production area in the Great Ruaha Basin within SAGCOT, data is collected from documents and 114 informants. This study finds that irrigation did not significantly contribute to rising paddy production in the case study. Prioritizing the downstream national park and the energy sector, the government periodically cut down the water access of the case-study irrigation scheme, which exacerbated water stress. Moreover, though farmers widely shifted to intensive farming and used hybrid seeds, mainly, the high-income groups ensured and increased the crop yield and profit. The-low income groups encountered crop failure and, due to rising production costs, debt. Many of them left farming, impoverished, and sought to secure subsistence through wage laboring. This study discusses the shortcomings of the transitions from traditional to intensive farming and from farming to employment as climate change adaptation strategies and draws critical policy-relevant conclusions.

Keywords: climate change, adaptation, intensive agriculture, growth corridors, Tanzania

INTRODUCTION

Anthropogenic emissions of greenhouse gases are warming the planet (IPCC Intergovernmental Panel on Climate Change, 2014b; IPCC Intergovernmental Panel on Climate Change, 2019). Temperatures have recently reached new record levels in the Indian Ocean, one of the primary storages of the earth's heat imbalance (Cheng et al., 2020). This change has also risen the frequency of rare cyclones, which was linked to the Australian bushfires of 2019–20 on the ocean's eastern coast and brought about exceptionally wet seasons on the western in East Africa (Cheng et al., 2020; Abram et al., 2021; Australian Meteorological Agency, 2021). As a result, East Africa experienced one of the warmest years in history in 2019; unusually high rainfall and consequent floods adversely affected over 2.8 million people, while more than 280 died (UN United Nations, 2019). This extreme also prompted the desert locus outbreak in Kenya and the Horn of Africa, spreading southward, with swarms of insects destroying croplands within only hours of their arrival (Climate Signals, 2020; National Geographic, 2020; IPP Media, 2021). This situation is about to worsen, with the UN agencies forecasting the continental warming to exceed 2°C by the mid-century and the frequency of rare cyclones, heavy rains, and natural disasters to further increase (IPCC Intergovernmental Panel on Climate Change et al., 2014a; UNFCCC United Nations Framework Convention on Climate Change, 2020; WMO World Meteorological Organization, 2020). These unequivocally devastating climate impacts on the already vulnerable food production and livelihoods in East Africa make adaptation an urgent response.

Climate impacts manifest in various forms and intensities in agriculture, to which farmers have varying capacities to adapt. Some impacts are sudden and extreme, termed shocks by climate researchers, often causing large-scale crop failures and leaving thousands of casualties and displaced people (IPCC Intergovernmental Panel on Climate Change et al., 2014a). Adapting to shocks is challenging; continental and global action is needed to limit greenhouse gas emissions to potentially mitigate warming, and thus, the prevalence of such extremes in the first place (Baarsch et al., 2020). But other climate impacts develop gradually and are not as intense. For instance, across most parts of Africa, temperatures have risen slowly by about 0.5°C in the last 50–100 years (IPCC Intergovernmental Panel on Climate Change et al., 2014a). This slow warming nonetheless put natural resources and crops under stress, the term for the gradually arising and often predictable climate impacts. Examples include groundwaters becoming depleted and rivers, lakes, and dams drying off, subsequently accelerating soil salinization and making croplands inarable, especially in semi-arid and intensively farmed areas (Herbert et al., 2015; Okur and Örçen 2020). Additionally to such stress on land and water resources, rainfall and temperature changes are moving beyond the levels that crops and livestock can tolerate, thus directly impacting agricultural production (Thornton et al., 2009; Thornton et al., 2014; Pereira 2017). As a result, staple food production is predicted to fall by a third by the end of this century and aggravate food insecurity in Africa (Lobell et al., 2008; IFPRI International Food Policy Research Institute, 2009; Schlenker and Lobell 2010; Lobell and Gourdji, 2012). In drought-prone countries, the number of undernourished people has already risen by 45.6 percent since 2012 (UNFCCC United Nations Framework Convention on Climate Change, 2020). Low-income groups are most vulnerable to climate shocks and stresses, as with decreasing food production, their income and wellbeing will also further decline (Boko et al., 2007; Arndt et al., 2012a).

The famine-inducing droughts in East Africa and the Horn since the late 2006 coincided with the global financial crisis of 2007–08, influencing African governments to embark on a "green growth" approach that agricultural growth has to be environmentally sustainable to avert new crises (OECD Organization for Economic Cooperation and Development, 2009; OECD Organization for Economic Cooperation and Development, 2011). One of the core ideas in this approach is that crop intensification with integrated biotechnological and market-based solutions can address environmental problems, and for this, private-sector investment into agriculture is necessary. Though green growth was endorsed globally in 2012 at the UN Conference on Sustainable Development in Rio de Janeiro (Rio+20), African governments and the global private sector decided to implement it in Africa earlier: the 2008 United Nations Private Sector Forum and the 2010 World Economic Forum on Africa influenced the designation of agricultural growth corridors, focused areas of expanded land use, investment, and trade (Nogales, 2014). By improving the management of natural resources and boosting food production, investments are envisioned to pull 50 million people out of poverty until 2022 and feed two billion people until 2050 (NEPAD New Partnership for Africa's Development, 2013; USAID United States Agency for International Development, 2020).

However, research-based evidence supporting the green growth idea is limited and not unambiguous. Since agriculture accounts for as much as 30 percent of the atmospheric CO_2 emissions, efficient input use through crop intensification and advanced waste management can potentially sink this emission and alleviate climate stress in agriculture (Beddington et al., 2012; Lal, 2016). But efficient input use and natural resource management locally do not necessarily lead the growing stress on these resources and food production stemming from a globally changing climate to sink. Also, regardless of how efficient these methods are, land use expansion accompanying crop intensification may even increase emissions instead of decreasing. Besides, the birth of growth corridors during a financial crisis is not coincidental. As critical scholars have argued, by the end of the 2008 crisis, rising food prices made food an attractive business for global corporations, pulling them to Africa for production and export (EU European Union, 2015; Buseth, 2017; Hall et al., 2017; Mdee et al., 2020). In this business-driven context, whether climate adaptation by the low-income groups will materialize pulls this study's attention into exploring one of the leading corridors in the continent.

One of the first corridor showcases in Africa is the Southern Agricultural Growth Corridors of Tanzania (SAGCOT), inaugurated by the Tanzania government in 2011 as its commitment to achieving agricultural green growth (SAGCOT, 2012a). The corridor area spans one-third of Tanzania (300,000 square kilometers), where almost a hundred official “partners” (investors, banks, input suppliers, food processor-traders, and donors) operate (SAGCOT, 2011b; SAGCOT, 2018). Investors acquire lands from the government to set up private farms, while other companies are commodity suppliers and financiers, distributing seeds, agrochemicals, and loans to both corporate and existing small producers. SAGCOT envisions to “sustainably intensify agriculture for smallholder and commercial agriculture alike, while simultaneously conserving the natural resources base that supports agriculture” and fostering climate adaptation (SAGCOT, 2012a: ii). In the center of this vision, the government emphasizes irrigation (bio)technologies, and employment (ESRF Economic and Social Research Foundation, 2018): while irrigation is the chief strategy to address climate stress on water resources, SAGCOT spans Tanzania’s largest river basin, the Rufiji (SAGCOT, 2011b; SAGCOT, 2013). It seeks to draw $3 billion investment into irrigation and waste management technologies (SAGCOT, 2012a; SAGCOT, 2012b). In terms of biotechnologies, drought-tolerant (hybrid) seeds are introduced for enabling producers to withstand intensified droughts while increasing crop production; for rice by an additional 2.2 million tons (SAGCOT, 2012a; CGIAR Consultative Group on International Agricultural Research, 2019). Lastly, by employing low-income farmers in private farms and nascent urban industries (after they abandon their lands), SAGCOT seeks to prosper and transition them into the middle-income status ($3 per capita per day and more) while propelling sectoral growth. Overall, by sustainably intensifying production, SAGCOT seeks to decrease CO_2-equivalent net emissions by about three million tons and pull 7–11 million people out of poverty by 2030 (URT United Republic of Tanzania, 2015b; URT United Republic of Tanzania, 2016a; URT United Republic of Tanzania, 2016b).

However, to whether crop intensification helps low-income farmers adapt to adverse climate impact and prosper, the literature provides polarizing answers. Significant research is available on hybrid seeds. Some studies explored their reproductive qualities, stress tolerance, and input dependence under diverse environments (Li et al., 2013; Assefa et al., 2015; Abberton et al., 2016; Ma et al., 2016). Others found that African farmers extensively adopted them to combat extreme droughts (Howden et al., 2007; Mengistu, 2011; Li et al., 2015; Elum et al., 2017; Komba and Muchapondwa, 2018). Still, their costs and whether the low-income farmers most vulnerable to climate stress can afford them are under-researched. This is relevant because certain hybrid varieties promoted in growth corridors, such as rice hybrids in SAGCOT, are bred for intensive farming and need increased investment. However, the low-income farmers in Africa often seek to cope with dry periods by shifting to low-investment and low-return farming instead of sowing seeds requiring high investment for high returns (Rosenzweig and Binswanger, 1993; Lema and Majule, 2009). This strategy protects them from risks, such as debt, since drought tolerance of these seeds has limits; they cannot perform their full productive features and bring high returns under extremes (Howden et al., 2007). In this context, expanded and improved irrigation as the chief adaptation strategy of the Tanzanian government is promising. But findings also show that government investments to expand and modernize irrigation have incited conflicts over land and water, reallocated from some users to others (Harrison and Mdee, 2017; de Bont et al., 2019). Moreover, strict water regulations enacted in river basins to promote efficient water use restricted agricultural water access and favored nonagricultural sectors, such as tourism and energy, aggravating these conflicts (Juma and Maganga, 2004; Mehari et al., 2009; England, 2019). Exploring whether such resource scarcity and conflicts persist and possibly prevent low-income farmers from withstanding droughts while they intensify farming is an interest of this study.

The potential of employment as adaptation is similarly disputed in the literature. Studies showed that farmers often prefer to diversify their income without rural outmigration to adapt: by diversifying land use and crops (Townsend, 1995; Bradshaw et al., 2004; Zonneveld et al., 2020); selling assets and livestock kept as microinsurance (Kazianga and Udry, 2006); and seeking local short-term employment (Paavola, 2004; Eriksen et al., 2005). Only when these strategies are inadequate, they consider temporary and short-distance rural outmigration for employment (Stark and Bloom, 1985; Henry et al., 2004; Black and Collyer, 2014), and permanent migration is a last resort (Banerjee and Duflo, 2011). However, opinions are divided on whether such transitions from farming to employment and migration are adaptation. Some scholars argued that rural and urban employment helps the affected people recover as long as household resettlement capacities and skills allow (Barnett and Webber 2010; Piguet, 2010). Others opposed that household decisions for rural outmigration for jobs are usually radical outcomes of climate impact, rather than decisions made before devastating impacts occur, and indicate worsened livelihoods (Brown et al., 2007; Brown, 2008; Warner and Afifi 2014; Adger et al., 2015). Whether local climatic variabilities are indeed behind the globally rising internal and crossborder migration is also debated (Hunter et al., 2015; Hoffman, 2020; Mueller et al., 2020; New York Times, 2020). The findings show that the drivers of rural labor transition and outmigration are nuanced and contextual, which this study pays attention to.

Overall, this study explores how the transition to irrigated intensive farming influences food and income security and the tendencies of agrarian households to leave farming for wage laboring and migration in Tanzania and whether such transitions can be considered adaptation. The definition of the concept of adaptation draws from the IPCC Intergovernmental Panel on Climate Change et al. (2014a): the process of adjustment to actual or expected climate and its effects. This process entails efforts to “moderate or avoid harm or exploit beneficial opportunities” arising from changing climatic conditions (ibid: 5). Since this definition is broad and allows multiple interpretations, this study selects an agrarian political economy lens to evaluate and interpret adaptation. This lens postulates that the transition to intensive commercial farming heightens rural inequalities, and new classes, such as laborers and migrants, naturally emerge, but farmers start falling into these classes as a result of worsened livelihoods (Bernstein, 1977; Bernstein, 1988; Griffin et al., 2002; Akram-Lodhi et al., 2006; Bernstein, 2010; Vicol et al., 2018). Based on this lens, the central hypothesis of the paper is: if the shift to intensive farming sustained crop yields and prospered livelihoods during erratic weather, farmers would not have to abandon their lands to seek jobs and migrate. To support this hypothesis, this study focuses on whether farmers, especially the low-income ones, justify the outcomes of such livelihood transitions as becoming better off or impoverished. Hence, the success of intensive farming is evaluated based on its ability to benefit the lowest-income groups and sustain their livelihoods.

Methods include empirical research conducted in southern Tanzania during the 2016–17 agricultural season. This season had erratic weather following the 2015–16 drought that prolonged into 2017. The potential of irrigated intensive farming as adaptation must be evaluated during such adverse periods. The case study is the Madibira irrigation scheme, constructed in 1998 in the Great Ruaha River Basin. This scheme is one of the major rice supply areas prioritized by the government for public irrigation investments. Mixed methods are used: document analysis, semi-structured and in-depth interviews, and surveys with 114 farmers. Interview data spans farmers' land sizes, production costs, loan sizes, harvest levels, marketing strategies, income sources, climate adaptation strategies, and livelihood changes over the years to interpret the drivers and outcomes of such change based on their perspectives. Harvest data is available from only 81 farmers. The 2017 harvest data is compared with the pre-intensification average of 4–5 tons per hectare in Madibira. The main level of analysis is the land in the scheme as an income source, and labor to the extent it supplements or substitutes such land-based income.

This paper is structured as follows. Section *Climate Impact in the Context of Staple Food Production in Tanzania* reviews the literature on climate stress and shocks in agriculture and finds that intensive agriculture has not significantly improved livelihoods in Tanzanian river basins. Section *Results: The Economic-Environmental Tradeoffs in the Great Ruaha Basin, 1998–2017* provides the results on irrigation, hybrid seeds, and the transition from farming to employment as potential adaptation strategies, along with the harvest and income data, identifying problems in this context. Finally, Section *Conclusion* discusses the results in the light of the literature, outlines the contribution of this study, and suggests avenues for further research. The findings align with the political economy literature: irrigated intensive farming mainly benefits the land-rich groups who are already able to withstand climate stress. Smallholders and middle-scale farmers leaving farming to work for the wealthier rural classes encounter worsened livelihoods. Hence, as long as intensive farming and employment opportunities arising in this context heighten rural dichotomies, they cannot be considered adaptation.

CLIMATE IMPACT IN THE CONTEXT OF STAPLE FOOD PRODUCTION IN TANZANIA

Tanzania is one of the fastest-growing least developed countries and transitioned from low- to lower-middle-income status in 2020 (World Bank, 2020), though its economy remains highly vulnerable to climate impacts. Temperatures have been variably increasing and changing precipitation across the country: in northeastern highlands, the mean, maximum, and minimum temperatures increased, leading to longer-than-average rainfall seasons with an earlier onset and late cessation of rains (Lema and Majule, 2009); in eastern Tanzania, rains increased by up to 50 percent, leading to higher frequency and severity of floods (Paavola, 2008; Kijazi and Reason, 2009); and southwestern highlands area (where this study is conducted) experienced decreasing rainfall and prolonged dry seasons (Kahimba et al., 2015). Studies associated the increasing frequency and severity of droughts and floods with climate change and agreed on the paralyzing and poverty-inducing effect of this change on livelihoods (Kijazi and Reason, 2009; Shemsanga et al., 2010; Kahimba et al., 2015; Irish Aid, 2018). Model projections revealed that if the temperature increase reaches 2°C by 2050, staple food yields (maize, sorghum, and rice) will further substantially decrease, leading to chronic food insecurity, especially in the southern highlands regions (Mbeya and Dodoma) affected by droughts (Rowhani et al., 2011; Arndt et al., 2012a; Kahimba et al., 2015).

Recurrent extreme droughts and rains since 1993 have influenced the present policymaking in Tanzania. First, the El Niño Southern Oscillation of 1993, followed by the 1997–98 La Niña, caused heavy droughts in some regions (Kahimba et al., 2015). A prolonged drought returning in 2005–06 impaired growth in agriculture and the overall economy, as the government reported (URT United Republic of Tanzania, 2007). Then, in 2010–11, heavy rains associated with El Niño prompted flooding in Morogoro and Dodoma, destroying infrastructure and human settlements. The 2015–16 drought, which this study covers, was "the worst El-Niño" until that year, as the Tanzania Meteorological Agency advertised (FAO Food and Agricultural Organization of the United Nations, 2016: 1). It resulted in massive crop losses, especially for staple crops, such as rice and maize, and livestock deaths, while food prices spiked, driving food insecurity across the country (FAO Food and Agricultural Organization of the United Nations, 2016). As the delayed onset of rainfall and early cessation of below-average rainfall continued in 2017, food shortages persisted: only from January 2016 to January 2017, maize prices doubled in Arusha, increased by 25 percent in Dar es Salaam, and generally reached high levels across the country (FAO Food and Agricultural Organization of the United Nations, 2017). This situation led the Economist Intelligence Unit to forecast the annual inflation rate to rise from 5.2 to 7.2 percent from 2016 to 2017 (Irish Aid, 2018).

The Tanzanian government acknowledges recurrent heavy floods and droughts as threats to food and income security and took four steps to mainstream climate change adaptation into its economic and agricultural policies. First, it designated the National Adaptation Program of Action of 2007, adhering to the United Nations Framework Convention on Climate Change guidelines of 2001, and prioritized agriculture as the most climate-sensitive sector (URT United Republic of Tanzania, 2007; Majule et al., 2014). Second, the National Climate Change Strategy of 2012 and the related sector-specific

Nationally Appropriate Mitigation Actions emphasized the necessity to mitigate climate impacts. Three, climate change is mainstreamed into the National Strategy for Growth and Reduction of Poverty, a cross-sectoral policy focused on poverty alleviation. Four, the Agricultural Environmental Action Plan (2011–17) prepared by the Ministry of Agriculture, Food Security, and Cooperatives emphasized environmental protection in the agriculture sector development planning (Majule et al., 2014). These four principal policy actions advised irrigation (and water harvesting), drought-tolerant seeds, and crop and income diversification as the leading adaptation strategies (ESRF Economic and Social Research Foundation, 2018), though significant problems arose in implementation.

Irrigation in river basins as the priority adaptation strategy of Tanzania has been on the top of the policy agenda since the 1970s, without succeeding in the desired expansion and efficiency outcomes. Tanzania has abundant water bodies, feeding its world-known rich ecosystems and wildlife, though only five percent of the potentially irrigable lands are under use (Majule et al., 2014). Such underuse influenced the government since the early 1970s to aim to unleash the full potential of its river basins by expanding irrigation in order to transform production from smallholder to highly productive commercial farming. The National Irrigation Master Plan of 2002 sought to expand irrigation to 29.4 million hectares, but until 2013, only 450,392 hectares were realized (URT United Republic of Tanzania, 2002; URT United Republic of Tanzania and JICA Japanese International Cooperation Agency, 2013). During the 2015 elections, expansion to one million hectares by 2025 was again on the top of the lead party's (Chama cha Mapinduzi, CCM) election agenda (URT United Republic of Tanzania, 2016a; URT United Republic of Tanzania, 2016b; JICA Japan International Cooperation Agency, 2018). Recently, the National Rice Development Strategy Phase II (2019–30) endorsed irrigation expansion for rice from 1.1 to 2.2 million hectares and emphasized its importance for climate adaptation in this subsector (URT United Republic of Tanzania, 2019), though the progress has been slow (USDA United States Department of Agriculture, 2021). Low public investment and lack of administrative capacities played significant roles in such slow progress (JICA Japan International Cooperation Agency, 2018).

In the lack of systematic irrigation expansion, common adaptation strategies among farmers had limited success during dry spells and adverse environmental ramifications in the past. Encroaching on wetlands to cope with water stress has been prevalent, depleting water resources and degrading ecologically rich river basins (Kikula, et al., 1996; Paavola, 2008; Kangalawe and Lyimo, 2013; Munishi and Jewitt, 2019). To fight water stress and increased land infertility, farmers switched to hybrid seeds and intensified fertilizer use, but harvest losses remained as high as 50 percent during dry spells (AATF African Agriculture Technology Foundation and COSTECH Tanzania Commission for Science and Techology, 2010; Shikuku et al., 2017; Komba and Muchapondwa, 2018). Government officials and extension agents lacked the budget and skills to improve land use management (Shemdoe et al., 2015; Pardoe et al., 2018) and passed on short-term solutions that did not foster long-term adaptation (England et al., 2018). The consequent failure to turn intensive farming sustainable came at the cost of the government expanding conservation areas (instead of irrigation) and expelling smallholder agrarian groups from river basins to give their land to companies that could invest in irrigation (Bergius, 2016; Buseth, 2017; Bergius et al., 2020).

Lastly, crop and income diversification helped farmers only to the extent they had recourse to them in supportive capacities instead of abandoning farming for employment and migration. In a case study in Kilombero, about half of the farmer population had such additional local income sources (Herrmann, 2017). After harvesting and selling crops, temporary migration for jobs in charcoal, timber, and brick production in nearby urban and rural areas has been common (Paavola, 2004; Paavola, 2008; Eriksen et al., 2005). The rising intensity and recurrence of climate stress turned such seasonal migration permanent, which did not significantly improve livelihoods (Warner and Afifi, 2014). Some low-income farmers failed to survive devastating crop and income losses after being exposed to climate extremes only once (Lema and Majule, 2009; Kahimba et al., 2015). Moreover, they found only low-income jobs, while mainly the existing better-off farmers diversified their incomes into profitable nonagricultural businesses, further prospering (Kahimba et al., 2015). These findings from the literature thus far support this paper's central hypothesis that if intensive farming stabilized and prospered livelihoods during erratic weather, farmers would not abandon their lands and migrate to seek jobs. The following sections dive into empirical insights to assess this argument.

RESULTS: THE ECONOMIC-ENVIRONMENTAL TRADEOFFS IN THE GREAT RUAHA BASIN, 1998–2017

Irrigation as Adaptation

In the Great Ruaha River Basin of Tanzania, climate stress in agriculture is significantly about water, which the government seeks to address through irrigation. However, a neglected tradeoff in this context is that the extreme weather episodes in the last decades have adversely affected not only rainfed farming but also irrigation due to recurrent and intensified river droughts in this basin. The years of droughts coincide with the years of below-average rainfall driven by El Niño and La Niña weather events. Based on the Tanzania Meteorological Agency (TMA) data (2016), the basin region (the Mbeya Region) has experienced new rainfall extremes in 1986, 1993, 1998, 2005, 2011, and 2015 as **Figure 1** shows (TMA Tanzania Meteorological Agency, 2021). The El Niño Southern Oscillation prompted prolonged droughts in 1992–93 and 1997–98 (Kijazi and Reason, 2009). From 1998 until 2005, most parts of the country, including the Great Ruaha Basin, experienced at least two consecutive droughts, with delayed rainfall onsets and unevenly distributed and below-

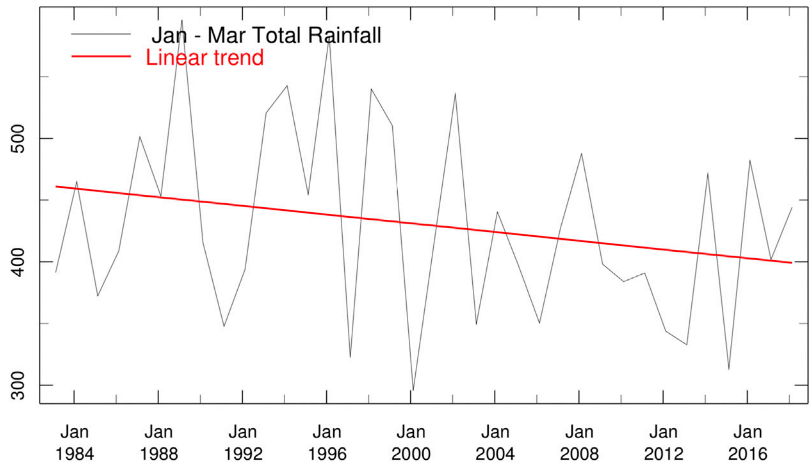

FIGURE 1 | Historical rainfall averages and anomalies in the Mbeya Region.

average rains (Kijazi and Reason, 2009). In 2014–15, another drought was caused by "the worst El-Niño" until then, as the FAO (2016: 1) reported, which extended into late 2016, with devastating consequences for livelihoods.

The climate data excerpted from the TMA database is consistent with farmers' perceptions of historical rainfall changes. The interviewed farmers argued that since the first paddy irrigation in 1998 (when the irrigation scheme was constructed), rains have been falling with more extended delays, with less precipitation, and ceasing earlier than usual. Especially the 2015–16 drought was felt strongly: as the annual report compiled by the scheme authorities confirmed, "the 2015–16 rainfall crisis severely affected farmers in the village and caused crop failures" (Annual Report 2016/17). Farmers contended that many of them had encountered crop failures this year, some already at the beginning of this season, due to the delayed rainfall begin; the seedlings had desiccated before sprouting and yielding crops. Consequently, they could not generate sufficient income to afford basic livelihoods needs, such as food and travel. These dramatic outcomes influenced the National Food Reserve Agency and the World Food Program to plan emergency food purchases in the region to secure rural income and store rice (staple food) in national warehouses to prepare for potential food shortages.

Despite the insights pointing to a strong connection between climate events and local rainfall extremes, Tanzanian policies have mainly focused on the potential role of the growing agriculturalist population in exacerbating water stress in river basins and sought to address this. This misplaced focus was to some extent driven by increasing water competition between water users, leading them to lobby for expulsion of smallholders out of the Great Ruaha Basin. Two decisive events that escalated this discourse were, first, the river's disappearing water flow for the first time in 1993 and then, the Mtera and Kidatu dams (meet for more than half of the country's power demand) entirely drying out in 1998, which caused days-long blackouts and paralyzing impacts on the economy (SMUWC, 2001). Scholars found that the local farming, hunting, and tourism businesses alleged small farmers as the main cause of the recurrent droughts in 1998–2005 (Lankford et al., 2009; Walsh, 2007; Walsh, 2012). Hydrological studies did not confirm the veracity of these allegations: the UK-funded project called Sustainable Management of the Usangu Wetland and its Catchment (SMUWC), one of the few and the most informative accounts on the hydrological change in this basin, listed agricultural water use as one of the potential drivers of the sporadically receding river flows, without making a firm statement (SMUWC, 2001). Nevertheless, in 2005, upon his election, president Kikwete acknowledged these claims, ordering "immediate urgent action" to revert the water crisis, as Walsh (2012) quoted, which included conservation area expansions to repel smallholders off the basin. Neither this decision nor studies examining this political discourse paid attention to the potential impact of the 1998–2005 climate events on this hydrological change.

The case study (the Madibira irrigation scheme) as a large-scale smallholder irrigation project played a critical role at the heart of this basin water debate, pulling hostility from the local business circles. The scheme construction was approved in the early 1990s when the government embarked on irrigation expansions to foster rural food and income security (SMUWC, 2001). The scheme abstracts water from the Ndembera River, one of the three major tributaries of the Great Ruaha (along with the Kimbi River and the main branch of the Great Ruaha River) before it flows into the Ruaha National Park (**Figure 2**). Its construction started in 1993 and ended in 1998, coinciding with the years of the two most dramatic river droughts, inevitably accentuating its potential role on the river droughts. At the end of the 1998–2005 droughts, a paper drafted by a local tourism company addressed this scheme as one of the causes of the droughts and accused the African Development Bank of funding this scheme without an environmental impact assessment and bringing "huge number of migrant people associated with rice farming" to this area (Fox, 2004: 4).

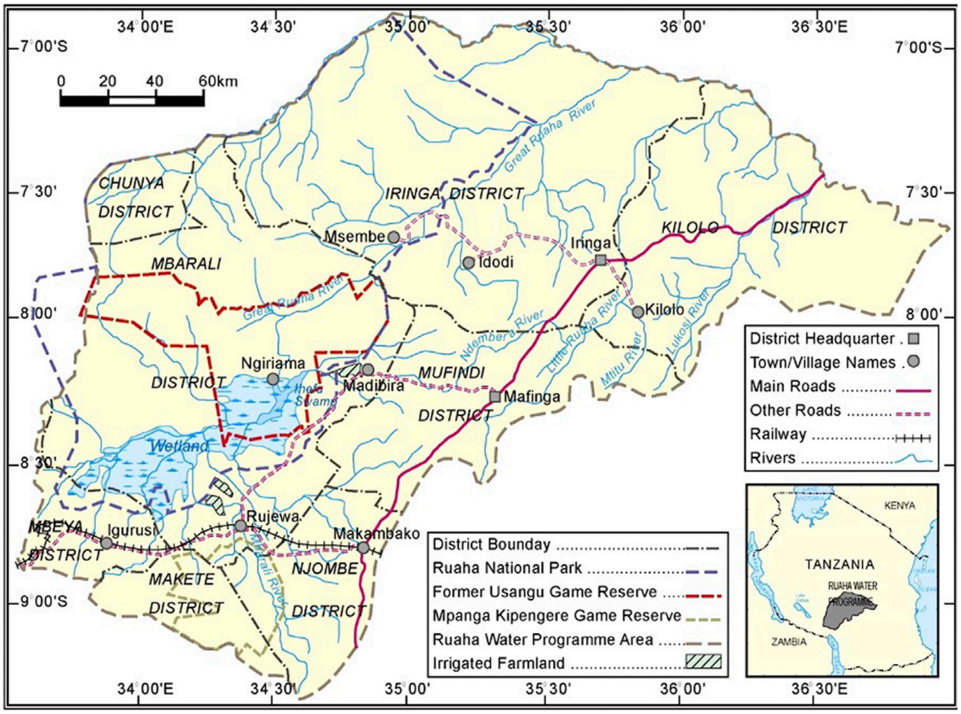

FIGURE 2 | Case study area (Madibira) within the Great Ruaha Basin Source: Mwakalila (2011).

Scholars claimed that this paper was backed by the state-owned Tanzania Electric Supply Company, which manages the dams, accusing the scheme and farmers of the desiccated river and the countrywide electricity crisis, allegedly attempting to veil its own water mismanagement of the dams (Machibya et al., 2003; Yawson et al., 2003; McCartney et al., 2007). This paper was influential upon the president's approval of a game reserve expansion in 2006, followed by the national park expansion encircling the reserve area in 2008 and the banning of agriculture therein (Walsh, 2012). The military pitched camps to evict agrarian groups and burned homes and sheds to ensure that farmers left and herders with their 300,000 cattle moved to the coastal region designated for them (IWGIA International Work Group for Indigenous Affairs, 2016). Two of the six dismantled villages (Mapogoro and Ikoga) were relocated to Madibira, folding its farmer population.

Interviews with farmers and the village chairpeople showed that the increasing farmer population due to this inter-district migration led the land and water demand in the Madibira irrigation scheme to rise instantly. But at the same time, with the Water Resources Management Act of 2009, the government enacted a formal water rights system to restrict water access in irrigation schemes, not only uncontrolled small-scale water use outside them. Water rights were first introduced in 1993 following the river drought this year to promote wise water use. Rights as statutory titles indicated the water volumes that water users are authorized to abstract from rivers, while fees, calculated based on these authorized volumes, had to be paid by them (Koppen et al., 2004). However, scholars found that the outcome of this experiment was unsatisfactory: basin officials lacked administrative capacities to monitor and sanction abstractions according to rights, and the system did not prevent the Great Ruaha from periodically drying and causing water scarcity (Koppen et al., 2004; Maganga et al., 2004). Still, with the 2009 act, the government renamed water rights as water permits and permanently passed them to restrict irrigation within irrigation schemes, in addition to scaling down agricultural land and water use outside them, and prioritized the Great Ruaha's flows into other sectors, though irrigation has also been a policy priority for decades.

Though the permits are not updated frequently, interviews showed that basin authorities periodically cut off or decreased irrigation water access during dry spells (when farmers need water the most) and continually increased the permit fees. The Madibira irrigation scheme received its final permit in 2013, allowing water abstraction from the Ndembera River from November to October every year. As the scheme's irrigation officer reported, the permit fee gradually increased from TSH7 to 11 million until 2016, and further changes followed the drought this year (Key informant 1, December 12, 2016). On the one hand, in 2016, basin authorities ordered him to halve the scheme's water abstraction from 7.5 to 4 cubic meters per second to retain water in the riverbed, although the permit fees would further rise in the same year. The Annual Report 2016/17 supports this statement that decreasing the scheme's water abstraction is necessary "to restore the perennial water flow of the Great Ruaha River, which will be prioritized." On the other hand, additionally to halving water abstractions, from 2017 onward, the scheme received water only from January to July, with a five-month cut in the irrigation period. However, as farmers indicated, paddy cultivation traditionally requires a longer time, from December to July, from seedling preparation until harvesting. The late cultivation by one month in January means potential harvesting delays into August, when farmers needed but lacked water due to the end of irrigation and cessation of rainfall, both in June. Together with the increased permit fee, water restrictions heightened the risk of crop loss and strained many livelihoods.

These findings show that irrigation as a climate adaptation strategy has limits in practice. Though the Tanzanian government has hailed irrigation for improved food and income security since the 1990s, it also took contradictory steps to restrict it, bringing about land and livelihood losses. This threat retains its significance since the government neither recognizes climate impact on natural resources nor the agricultural and nonagricultural sector interests standing in conflict in the context of the ongoing basin debate that is political in nature. This omission countervails the prospect of expanded irrigation to foster adaptation for small farmers. Another contradiction in this context is that while the water stress has been blamed on farmers, a narrative which drove conservation area expansions and strict water regulations, in another context promoting the shift to intensive farming, this stress has been considered a consequence of climate change. Though they themselves cut down the Madibira irrigation scheme's water access, backing the claims that farmers used too much water, two authorities argued that the rising water stress resulted from "global warming" but would be "compensated through efficient commercial agriculture," with the use of the drought-tolerant hybrid seeds (Key informants 2 and 3, December 13, 2016). Various potential reasons for water stress being reworked in different contexts is another political insight that points to limits of irrigation as adaptation. The next section explores whether the shift to intensive paddy farming has indeed been rewarding in this context.

Intensive Paddy Farming With Hybrid Seeds as Adaptation

In SAGCOT, intensive paddy farming with drought-tolerant seeds is promoted as a way to foster climate adaptation and food security. Though some multinational SAGCOT partners, such as Monsanto and Syngenta, sell genetically modified seeds across the corridor, specifically in the rice subsector in the Mbarali cluster, most drought-tolerant rice seeds are bred by the national agricultural research institutes that have received donor support since the 1980s. These seeds are hybrid varieties, combining productive and morphological qualities of traditional and genetically modified seeds, and advertised by the government and partners to sustain and increase crop yield with less water and in a shorter time than usual. In addition to their productivity features, some offer an enhanced taste, which contributed to the widespread acceptance of some varieties by Mbarali farmers since 2013. The most successful hybrid rice seed combining high yield with semi-aromatic flavor is SARO5 (termed TXD306), bred by the Agricultural Research Institute Chollima-Dakawa, with TXD (Tanzania Cross Dakawa) indicating its origins. Other hybrids, such as Katrin (IR54 and IR64), bred by the Kilombero Agricultural Research Institute (KATRIN) in Morogoro, are more productive than SARO5 but did not succeed due to their lack of aroma (most farmers produce rice for both cash and household consumption). Still, farmers locally call SARO5 "the export variety" since it is highly demanded in export markets and brings cash through mass production. Meanwhile, the traditional variety is preferred mostly when taste and domestic market supply are farmers' priorities.

In Madibira, SARO5 has succeeded, with an above 90 percent acceptance rate by commercial farmers. Various informants (farmers, local authorities, and companies) confirmed that this variety indeed yields more paddy. Moreover, though it requires irrigation for such high-yielding performance, SARO5 crops mature faster, enabling adaptation to shortened irrigation and rainfall periods, for which they are considered drought-resistant. The government extension officers argued that SARO5 seeds can multiply the average paddy production under irrigation from the country average of 4–5 tons per hectare with traditional seeds to 8–9 under intensive farming and 12 under systematic rice intensification (SRI) (*kilimo shadidi*) (USDA United States Department of Agriculture, 2018). SRI is an intensive rice farming technique developed in Madagascar in the 1980s, which, under some conditions, can provide two times the yield with half of the amount of water required by some traditional seeds (Cornell University, 2020). Spreading the SRI practice along with expanded irrigation to increase paddy production from the countrywide traditional rainfed average of 1–2 tons per hectare is one of SAGCOT's subsectoral goals (SAGCOT, 2011a). Though progress has been slow: in Madibira, in 2017, only ten farmers practiced SRI, as confirmed by the extension agents. The interviewed farmers considered it a labor-intensive technique needing to count seeds and sow according to a linear pattern (instead of randomly planting in the field) and flatten the soil for which they lacked capital. Still, without SRI, SARO5 has fulfilled its increased production and decreased water requirement promises to some extent, which contributed to their widespread acceptance in a short time. As a farmer put it, "after seeing their neighbors harvest a lot and prosper, even those skeptical of this seed at first only cultivate it today" (Farmer 1, December 04, 2016).

The problem about the SARO5 seeds little mentioned in the scholarly and gray literature is that despite their attractive features such as reasonable price, less crop water requirement, and higher productivity than the local seeds, they need intensive fertilizer use. Tanzania does not have a strong fertilizer industry and imports fertilizers, making their intensive use expensive for smallholders. Therefore, fertilizer use across Tanzania has been low, only one to two bags per hectare to none (Majule et al., 2014). In comparison, Madibira farmers used three-four bags per hectare before shifting to hybrid seeds and seven and more after. Moreover, they used YARA fertilizers only. YARA is a Norwegian fertilizer company; it built a fertilizer terminal at the Port of Dar es Salaam shortly after becoming an executive SAGCOT partner and monopolized the fertilizer market by opening retail stores in rural areas. In Madibira, YARA salespeople were more active than the government-hired local extension agents; they frequently visited villages, organized farming workshops, and staged games with free fertilizers for the winners, successfully promoting own products. Also, the extension agents advised farmers to use only YARA fertilizers due to their "higher quality" (Key informant 4, July 13, 2017) and promoted the need to use at least seven bags of this brand fertilizers in the extension curriculum. Though farmers agreed to increase fertilizer use to sow SARO5 for increased production, production costs climbed as well: in the 2016–17 season, one bag cost TSH55,000 ($24) at the village salespoint, TSH40,000 ($17) directly from YARA, and TSH65–67,000 ($28–30) from intermediaries, all of which farmers considered expensive[1].

The shift to intensive farming with SARO5 seeds and increased fertilizer use increased production costs by 50 percent from TSH1.5 to TSH2.5 million ($1,100) per hectare on average, which was beyond the capacity of the most low-income smallholders to afford. This gave rise to loan dependence in Madibira: 60 percent of my informants were smallholders (with one-hectare landholding), and all of them had to rely on loans to engage in paddy cultivation. Though national banks, such as the National Microfinance Bank and Cooperative Rural Development Bank, have joined SAGCOT as partners to give out loans to smallholders, in the widespread lack of collateral to put up for the loan, smallholders in Madibira lacked access to them. The increased production costs thus worsened their dependence on local microfinance institutes and moneylenders (usually, the wealthy local settlers) who charged high interest rates, often exceeding 30 percent. Moreover, some moneylenders used strong-arm tactics to collect loan payments from debtors with low harvest and crop failure by seizing their crops, lands, and small properties at the end of cultivation seasons. Hence, by encouraging the smallholders, particularly the low-income ones, to intensify paddy farming and bear increased costs before establishing a robust microfinancing system, SAGCOT put smallholders at debt risk.

Interviews also cast light on an economic-environmental tradeoff in the shift to intensive paddy farming: farmers stated that they felt "forced to use fertilizers intensively" since the soil fertility steeply declined and soil salinization became a serious problem due to monocropping (Farmer 2, December 05, 2016). They argued that in the first years of irrigation in the scheme in the early 2000s, they harvested 4–5 tons per hectare of paddy without any inorganic fertilizers, which is allegedly nowadays impossible to obtain without multiple bags of fertilizers. Farmers added that intensified droughts accelerated soil salinization, exacerbating the impact of erratic weather on food production. Some findings in the literature align with this suggestion that droughts worsen soil salinity, while salt, in turn, prohibits water uptake by plants (Paul et al., 2019; Corwin, 2020). To address this problem, Tanzanian research institutes developed a salt-tolerant version of the SARO variety, called SATO, which is becoming a necessity for farmers to be able to sustain food production. These findings show that while attempting to nurture food and income security through a shift to intensive farming, the government and SAGCOT partners neglect the rising environmental and economic disadvantages that consequently put greater stress on livelihoods instead of alleviating it.

Harvest and Income Data

Whether intensified irrigated paddy farming is a rewarding adaptation strategy for smallholders to sustain and improve their livelihoods requires examining the changing harvest and income levels. This section sheds light on this change following the shifts to irrigated paddy farming in 1998 and to intensified irrigated paddy farming in 2013 in Madibira, focusing on the 2016–17 season, the fieldwork period.

In Madibira, paddy irrigation began with equitably allocated landholding to local subsistence-oriented farmers, one hectare per capita, to commercialize the existing paddy farming. With this size of land, the government sought to put smallholders, who in the region typically held only a few acres (one hectare is about 2.5 acres) (Franks et al., 2013), at the threshold of transition to middle-scale farming and raise their incomes. Interviews showed that though most landholders initially lacked capital and labor to farm such a scale without loans, their incomes and cultivation capacities gradually improved. The scheme office recorded that the scheme-level harvest average was 4–5 tons per hectare in 2004, increased from 1 to 2 tons per hectare before irrigation begun in 1998, the last year of the official harvest records kept by this office. During these years, an assessment study conducted by the government showed that average income rose from TSH145,000 to TSH360–400,000 per hectare in the same period (AFD African Development Fund, 2004). This study also pointed to livelihood improvements associated with harvest and income increases, measured by increased ownership of burnt brick houses, power generators, motorcycles, farming and milling machines, and village shops. Moreover, school enrollment rates rose, and farmers began hiring laborers, prospering, and creating jobs simultaneously (AFD African Development Fund, 2004). The scheme office argued that this scheme-level harvest average of 4–5 tons was maintained until the transition to intensive paddy farming in 2013. However, interviews revealed that some farmers prospered more than others; the low-income farmers that SAGCOT sought to benefit struggled and often failed to achieve and sustain this harvest level. This finding builds on another one that scheme farmers in practice held lands of diverse sizes—small, middle, and large-scale lands—despite the formal landholding rule requiring them to hold a maximum of one hectare per capita. And mainly, the middle- and large-scale farmers harvested a lot, thus pulling the scheme-wide paddy harvest average above the average of the smallholder subgroup, which this study focuses on.

Despite holding one hectare per capita on paper, prospered farmers have accumulated multiple hectares informally from others who succeeded less in irrigated paddy farming. Among 114 farmer informants, only 66, about 60 percent, were smallholders who held only one hectare. Middle-scale farmers

[1]The conversion rate on 14 January 2017: 1,000 Tanzanian shilling (TSH) = 0.44 United States dollar ($).

with 2 and 3 hectares were 19 and 6 percent of the population, respectively, while 3 percent held lands larger than 3 hectares. The largest-scale farmer held more than 20 hectares and the second-largest 7 hectares; such few very large lands pulled the landholding average among informants up to about 2 hectares. Surveys provided further data showing that farmers with larger landholdings also had higher amounts of additional income, drew more on household-external labor, and owned more properties and livestock, pointing to class division among farmers. Income-generating assets were unequally distributed: all land-rich farmers with 4–5 hectares and more owned big farm machines (tractors and combine harvesters), which they rented out to other farmers for income. In addition, they owned additional businesses, such as the few restaurants, bars, guest houses in the village, and rice milling facilities, engaging in food trade. Middle-scale farmers with 2 and 3 hectares had smaller properties, such as power tillers and village huts, selling food and household goods, hired laborers to relieve household labor shortages, and only occasionally drew on cultivation loans. In comparison, all smallholder informants (with one hectare) took loans; they sometimes hired day laborers to complete difficult tasks during harvesting and sometimes worked as laborers for extra cash. Their property ownership was limited to a few hens and cattle, small maize plots in the drylands, and home vegetable gardens. These assets secured food and income to some degree but did not ensure farming investments when the harvest levels were low following drought periods. Smallholders depended on the harvest from season to season to subsist and reinvest in farming, and low harvest triggered land loss and redistribution to the wealthier classes.

To provide a systematic understanding of how harvest translated into income and potentially improved livelihoods in 2016–17, together with informants, I coined four income thresholds based on the average market prices (**Table 1**). That year, prices were lower than usual due to the grain export ban introduced by the government. This ban led wholesale paddy prices for SARO5 to halve from TSH1.1 million per ton ($484) to TSH0.55–0.6 million per ton ($242–264) in 2015. In 2016–17, prices slightly increased but remained low at TSH0.75 million per ton ($330). Based on this average price, the profit threshold, at which the income barely covered the production costs (TSH2.5 million), was 3 tons per hectare. Farmers defined a harvest at and below this level as crop failure because based on the early marketing season price of TSH75,000 per sack, 3 tons generated only TSH2.25 million per year and zero to minus profit after average production costs were withdrawn. This harvest used to be the subsistence threshold in 2014–15 based on higher prices (TSH1.1 million per ton) and used to create TSH0.8 million profit per year ($352) and TSH2,000 per day ($0.9 per day). However, it generated only $0.3 per day in 2016–17. Decreasing prices caused this harvest level to become insufficient for subsistence.

The new subsistence threshold, at which the profit made a (minor) contribution to subsistence, became 4 tons per hectare in 2016–17. This harvest generated only TSH1.25 million per year ($550) and TSH3,000 per day ($1.3) in the subsistence range, allowing farmers to access a limited range of food and cover only the basic livelihood needs. The stabilization threshold, which enabled farmers to make a sufficient profit to sustain their livelihoods and replenish their farm investment capacities for the next season (2017–18), was 6 tons per hectare. This harvest generated TSH2 million profit per year ($880) and TSH5,000 per day ($2.4), enabling farmers to afford the children's education costs, access a broader range of food, undertake basic household renovations, and occasionally buy clothes and travel based on the local commodity prices. In addition, loan-dependent farmers could save some cash, thus needing to take smaller loans in the subsequent season.

The wealth threshold, only achieved through intensive farming (requires hybrid seeds, more than seven bags of fertilizers, and mechanized monocropping), was 8 tons per hectare. This is also the harvest level targeted by the government (i.e., 8–9 tons and above). A harvest in this range of 8–9 tons per hectare could indeed bring a profit of TSH3.5–4.25 million per year ($1,540–1,870) and TSH9.6–11.6 per day ($4.2–5.1), enabling farmers to generate farming investment for the subsequent season, overcome loan dependence, meet the household needs, save cash, and access a greater variety of food and some luxury goods. Smallholders sustaining this harvest level for a few years could potentially transform into large-scale farmers and diversify incomes into wealth-generating nonagricultural businesses rapidly, which have been SAGCOT's vision. However, smallholders did not achieve these harvest levels.

Despite the shift to intensive farming, the mean harvest was 5.6 tons per hectare for the informants with harvest data (n = 81)—much below the 8–9 tons goal and not significantly above the pre-intensification range of 4–5 tons per hectare. The difference between the highest and lowest harvest was significant; the highest was above 9 tons per hectare and the lowest below 1 ton, significantly deviating from the mean. Based on the increased production costs (TSH2.5 million per hectare) and below-average market prices, farmers would have to harvest much above the usual levels to be able to sustain their livelihoods; harvesting the same amount of paddy as in the previous year put them into a lower-income group.

TABLE 1 | Harvest-income thresholds for income generation in the case study, 2016–17.

Income threshold	Harvest (tons per hectare)	Annual income
Profit/Crop failure	3	0–TSH250,000 ($0–110 per annum) ($0.3 per day)
Subsistence	4	TSH500,000 ($220 per annum) ($0.6 per day)
Stabilization	6	TSH2 million ($880 per annum) ($2.4 per day)
Wealth	8	TSH3.5 million ($1,540 per annum) ($4.2 per day and above)

TABLE 2 | Landholding size of farmers according to their harvest levels, 2016–17.

	Crop failure (0–3 tons/ha)	Subsistence (4–6 tons/ha)	Stabilization (6–8 tons/ha)	Wealth (8–9 tons/ha)	Above 9 tons/ha
n = 81	9 farmers	34 farmers	30 farmers	6 farmers	2 farmers
Mean land size	2.2 ha	1.6 ha	2.5 ha	4.8 ha	2 ha
Minimum land	1 ha	0.6 ha	1 ha	2 ha	2 ha
Maximum land	4 ha	6 ha	7 ha	15 ha	2 ha
Landholders	1 ha (33%)	1 ha (53%)	1 ha (43%)	2 ha (50%)	2 ha (50%)
	3 ha (33%)	2 ha (29%)	4 ha (20%)	4 ha (33%)	4 ha (50%)
	2 ha (22%)	3 ha (9%)	2 ha (13%)	15 ha (17%)	—

*Percentages show the three largest subpopulation in each group. Smallholders hold only one hectare (italic). Among smallholders (*n *= 34), three are at the crop failure, 18 at the subsistence, and 13 at the stabilization range.*

A comparison of the harvest and land data shows that smallholders harvested less paddy and generated less income than large-scale farmers (**Table 2**). All large-scale farmers harvested above the mean of 5.6 tons per hectare: 6–10 tons per hectare, which enabled them to maintain their high-income status. Only two farmers harvested above 9 tons. One of them was a large-scale farmer who used fertilizers intensively: nine bags above the standard of seven. The other held middle-scale lands, one of the few people that invested in land leveling and external labor to practice SRI, as confirmed by the local extension agent. Thus, the highest income group generating $4.2 and more per day were middle- and large-scale farmers only. Farmers with larger landholdings than smallholders invested more in intensive paddy farming and better coped with erratic weather. Middle-scale farmers fell into both high- and low-income groups. For example, one middle-scale farmer rented three hectares and cultivated middle-scale for the first time and fully on loans in 2016–17, aiming to fold his income over a single season despite hitherto being a smallholder. Harvesting as little as 4 tons per hectare of paddy on average due to the erratic weather, his debt multiplied by several hectares instead, leading him to consider renting out his plot and seek employment in 2018. This case shows that the confidence in the drought-tolerant seeds put some farmers at a disadvantage by encouraging them to neglect the weather risks.

Among smallholders with harvest data (*n* = 34), the main group of interest in this study, corresponding to 42 percent of farmer informants, no one harvested above 6 tons per hectare. The majority, 53 percent, harvested 4–6 tons per hectare and stayed in the lower-middle-income group ($0.6–2.4 per day). Though they survived erratic rains, a few of them struggled to subsist because of paying back loans with high interest rates. Because of submitting a large portion of their harvest to local financiers for loan payments, they also could not add value to crops by warehousing paddy (to sell at higher prices at the end of the season) or milling it to rice that increase income per unit of harvest as land-rich farmers usually do. The second-largest smallholder population with 38 percent harvested 6–7 tons per hectare at the stabilization range, joining the upper-middle-income group ($2.4–3.3 per day). They generated sufficient cash to repay their loans and invest in farming in the subsequent season, thus decreasing their loan dependence, which should be considered a livelihood improvement. Only to a limited extent, intensive farming succeeded in moving smallholders into the government-defined middle-income status of $3 per day. Because only the middle- and large-scale farmers harvested above 7 tons per hectare, earning $3.3 and more per day, intensive farming mainly benefitted the already better-off farmers.

A minority of the informant population (9 percent) had crop failures with 3 tons per hectare and less, putting them into the lowest income group ($0–0.6 per day). Farmers who harvested below the average argued that this was due to erratic weather. For example, the smallholder with the lowest harvest anticipated a harvesting delay to September 2017 (the usual harvest time is July) and collected only 3 tons of paddy with zero profit (Farmer 3, July 09, 2017). She held low precipitation responsible for the crop failure: when the rains ceased and most people harvested in July, her crops were still not ripe and partially died. Another smallholder who collected a low harvest of 3.6 tons also pointed to insufficient rainfall, which he had anticipated before cultivation started (Farmer 4, July 14, 2017).

Narratives from all informants (*N* = 114) on livelihood transitions spanning a longer period since 1998 show that leaving farming to become laborers is impoverishment rather than adaptation. This is because all accounts explaining such transition involved poor harvest and debt, impelling people to abandon the scheme, liquidate their assets, farms, and livestock to pay for debt and look for jobs. For instance, an informant claimed "a life-ruining debt" had driven her family to give away their one-hectare plot in the scheme: she had harvested 4 tons of paddy and submitted all of this to a moneylender to pay her YARA fertilizer debt, and she and her husband started working as day laborers for the wealthier scheme farmers (Farmer 5, December 10, 2016). The village chairperson reported that the 2015–16 drought similarly affected many other livelihoods, leading hundreds of farmers to lease out their lands; "they did not migrate from Madibira but stayed and looked for work at the irrigation scheme" (Key informant 5, December 23, 2016).

The most common and available types of work were day and seasonal wage labor in the scheme, which could not compensate for farming in terms of income generation. Wages for day labor varied depending on the task (e.g., canal cleaning TSH2,000, harvesting TSH50,000). Seasonal wages covered multiple tasks, including land preparation, seedling transplantation, and harvesting, and ranged at TSH500–750,000 ($220–330) per hectare per season, below the subsistence threshold in 2016–17. Only farmers who additionally rented out their formal one-hectare landholding in the scheme at the average lease rate of TSH750,000 generated income equivalent to TSH1.25–1.5 million ($550–660) in the subsistence range. Despite such income established some livelihood security, paddy farming could bring much more cash, up to "multiple millions of shillings," as a local authority claimed (Key informant 6, June 11, 2017). Hence, farmers strived toward this goal even in the sight of weather adversity.

Once farmers became laborers, they found financial recovery difficult. The transition to employment was irreversible for many of them, even when they kept their landholding on paper. For instance, one laborer stated that she hoped to take cultivation loans "some time" again, but for the near future, she wanted to continue engaging in seasonal employment and petty commodity trading, considering these as securer income generation options (Farmer 6, December 10, 2016). Nevertheless, these options did not allow them to generate sufficient income to return to farming. Another laborer, a former farmer, asserted "a constant risk of collapsing" in his family and that he "constantly sought ways to escape this (poverty) cycle" but failed (Farmer 7, December 09, 2016).

CONCLUSION

This paper examined the livelihood effects of three key strategies that policymakers advise farmers for climate change adaptation in Tanzania: irrigation, drought-tolerant seeds, and employment in the context of intensive paddy farming in SAGCOT. Interviews were conducted in the Great Ruaha Basin shortly after the 2015–16 drought prompted by El Niño adversely affected this area but covered a longer period since the beginning of irrigation at the case study in 1998 to understand whether these strategies enabled smallholders to withstand droughts. The findings are to a significant extent consistent with the outcomes of the literature review: climate impact on natural resources and food production has been worsening in Tanzania (e.g., Lema and Majule, 2009; Arndt et al., 2012b; Warner and Afifi, 2014; Komba and Muchapondwa, 2015; Komba and Muchapondwa, 2018). Farmers indicated that the drought that year was more intense than in the past, with decreased rainfall starting later and ceasing earlier than usual. They also pointed to the potential impact of recurrent droughts on exacerbated soil salinity, a common type of land degradation in intensive farming. In this context, expectedly, irrigated intensive farming had limited benefits for the low-income farmers to cope with climate stress and sustain their livelihoods.

Irrigation can offer opportunities for dryland farmers affected by the rainfall decrease to adapt to water stress, thus contributing to food and income security, as the Tanzanian government depicted (SAGCOT, 2011b; URT United Republic of Tanzania, 2011; URT United Republic of Tanzania and JICA Japanese International Cooperation Agency, 2013; URT United Republic of Tanzania, 2015a; JICA Japan International Cooperation Agency, 2018). Documents collected and interviews showed that the transition from dryland to irrigated paddy farming with the construction of the irrigation scheme in the case study area in 1998 indeed increased the average paddy harvest from 1–2 to 4–5 tons per hectare. After that, asset ownership and living standards improved, which the government interpreted as progress toward poverty alleviation in the area, which the government interpreted as progress toward poverty alleviation in the area (AFD African Development Fund, 2004). However, this study also revealed that since then, despite intensified farming with SARO5 seeds with drought-tolerance features, the average harvest in 2016–17 following the drought remained 5.6 tons per hectare, only a little above the 4–5 tons per hectare average. This finding shows that the drought tolerance and productivity of the hybrid seeds are limited: adequate water still has to be available for irrigation to ease water stress and for these seeds to yield the expected high harvest (i.e., 8–9 tons per hectare).

In the water-energy-food nexus in river basins, unless water for food and rural income is a priority, the potential of irrigation as an adaptation strategy for farmers has limits. This is the case in the Great Ruaha River Basin: the existing literature already established that the government holds the upstream farmer population responsible for the drying river and compromises food production while seeking to enhance the water flows into downstream national park and energy sectors—an ongoing debate with significant political dimensions such as powerful interest groups competing for water (Maganga et al., 2004; Walsh, 2007; Walsh, 2012; England, 2019). The findings in this study provide relevant insights for this literature: while releasing abundant water during heavy rains, authorities planned to cut water abstractions of the case-study irrigation scheme by half and the irrigation season by 5 months following the drought when farmers needed water the most. The same authorities, denying the role of inequitable water allocation in exacerbating water stress, also used climate change as a buzzword to explain this situation. This shows that though climate impact on natural resources is an existing problem, this narrative sometimes eludes the nuanced and political drivers of water stress in river basins, pointing to further shortcomings of irrigation as adaptation where water is a conflict substance.

Limited water security leaves farmers no choice but to switch to the hybrid seeds to adapt to water stress and bear increasing costs by taking loans despite the risks associated with this move. Limited drought tolerance of the seeds aside, their fertilizer demand soaring production costs is a problem. The literature argued that hybrid seeds are one of the most common climate adaptation strategies among Tanzanian farmers (CIMMYT International Wheat and Maize Improvement Center, 2016; Komba and Muchapondwa, 2018; Lybbert and Paul, 2018; CGIAR Consultative Group on International Agricultural Research, 2019), but this does not tell much about their success in securing livelihoods, especially for the most vulnerable low-income groups. By showing that the low-income farmers could only engage in intensive farming with hybrid seeds through loans, which perpetuated debt and took a toll on livelihoods, this study adds to the existing but scant literature in this context. Attention is needed on the affordability of other hybrid seeds by the poorest farmers and how their livelihoods improve due to this seed choice to be able to draw conclusions on poverty alleviation. Further research avenues include assessing the environmental impacts of the hybrid seeds where land fertility is already low due to intensive farming.

One of the most significant findings that align with the theoretical agrarian political economy literature is that the transition to intensive commercial farming does not make all farmers better off (e.g., Griffin et al., 2002; Akram-Lodhi et al., 2006; Bernstein, 2010; Bernstein and Oya, 2014; Bernstein, 2016; White, 2018). This study found that farmers who prospered through irrigation gradually accumulated landholding informally and invested in profitable nonagricultural businesses. Only such land-rich farmers survived the 2015–16 drought and the reportedly low precipitation in the subsequent season, reaching the highest and above-the-average harvest levels. Meanwhile, the erratic weather only adversely influenced the small- and middle-scale farmers. In the best examples, small- and middle-scale farmers subsisted and stabilized their livelihoods while depending on cultivation loans in the next season again; in the worst, devastating debt impelled them to rent out their lands immediately after harvesting to pay up the debt. Hence, the shift to intensive farming heightened the rural inequalities as expected. Moreover, most such affected farmers remained settled in the case study area and looked for wage labor instead of migrating. Farmers left their plots involuntarily and found it difficult to create adequate capital to return to farming because the local wages hardly sufficed for subsistence. Hence, the transition from farming to employment, in this case, should be interpreted as worsening livelihoods.

Based on the findings, policymakers are recommended to consider alternatives to intensive farming, such as environmentally sustainable methods improving the soil fertility naturally. Seed varieties aimed at strengthening climate adaptation capacities should not perpetuate input and loan dependence. Also, attention to equitable land and water allocation in river basins is overdue. Finally, SAGCOT maintains a negative reputation in the scholarly literature due to malpractices in land-based investments (Exner et al., 2015; Greco, 2015; Bergius et al., 2020). However, in the staple food subsector, adjusting its focus to enable smallholders to hold land equitably, promote environmentally sustainable climate adaptation and cultivation strategies, and strengthen rural-urban trade for improved food distribution from surplus to deficit areas may help elevate its contribution to the national food and income security.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion 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.

AUTHOR CONTRIBUTIONS

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

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Analysing the Water-Energy-Food Nexus From a Polycentric Governance Perspective: Conceptual and Methodological Framework

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The Water-Energy-Food Nexus has emerged over the past decade as a useful concept to reduce trade-offs and increase synergies in promoting goals of water, energy and food securities. While WEF scholarship substantiates the biophysical interlinkages and calls for increased and effective coordination across sectors and levels, knowledge on conditions for effective coordination is still lacking. Analysing WEF nexus governance from a polycentricity perspective may contribute to better understanding coordination. In this paper, we propose a conceptual framework for analysing WEF nexus governance based on the Institutional Analysis and Development (IAD) framework and the concept of Networks of Adjacent Action Situations (NAAS). The interdependence among transactions for pursuing WEF securities by actors in different action situations generates the need for coordination for changing or sustaining institutions, policy goals and policy instruments that guide actions leading to sustainable outcomes. Coordination is attained through arrangements based on cooperation, coercion or competition. Coordination in complex social-ecological systems is unlikely to be achieved by a single governance mode but rather by synergistic combinations of governance modes. Particular coordination arrangements that emerge in a context depend on the distribution of authority, information and resources within and across interlinked decision-making centres. Further, integrating the political ecology based conceptualisations of power into the analytical framework extends the governance analysis to include the influence of power relations on coordination. Methodological innovation in delineating action situations and identifying the unit of analysis as well as integrating different sources and types of data is required to operationalise the conceptual framework.

Keywords: water-energy-food nexus, polycentric governance, coordination, governance modes, interdependencies, institutional analysis and development (IAD) framework, networks of adjacent action situations (NAAS)

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1 INTRODUCTION—WATER-ENERGY-FOOD NEXUS

The water-energy-food (WEF) nexus is promoted as a governance solution to complex resource management challenges. The WEF nexus concept serves multiple purposes—as an analytical tool, a conceptual framework, or a discourse (Keskinen et al., 2016). As an analytical tool, WEF nexus analyses typically include either quantitative or qualitative approaches or both in understanding the interactions and interdependencies among water, energy and food systems (Albrecht et al., 2018). However, as a normative governance concept to achieve policy coherence, the WEF nexus has had limited success—if any—so far. As a discourse, though, it has made a significant contribution in terms of framing or reframing the problem of resource governance, especially of water. The WEF nexus framed as a governance challenge (Pahl-Wostl, 2019) presents a unique framing of the challenge of resource governance where different societal goals implicit in the policies to secure water, energy and food security compete with each other for resources.

The concept of WEF nexus originated from a normative goal of identifying and implementing strategies for achieving water, food and energy securities that are crucial for human well-being, poverty reduction and sustainable development (FAO, 2014). The literature provides separate nuanced definitions for each of the three securities (Pahl-Wostl, 2019), but broadly spoken WEF security mainly refers to access to sufficient water, food and energy for human well-being. While the initial focus was on water as a key natural resource input essential for WEF securities (WEF [World Economic Forum], 2011; Pahl-Wostl, 2019; Simpson and Jewitt, 2019), the scholarly focus has since shifted to the interdependencies among various natural resources and the need for the sustainable governance of soil and biodiversity besides water as inputs for the respective securities as outputs (Müller et al., 2015; Pahl-Wostl, 2019). In contrast to the broad conceptualisation of WEF nexus, Albrecht et al. (2018) contend that methods and tools to quantify and assess WEF interlinkages have not been sufficiently developed and have mostly been "borrowed or adapted from the conventional disciplinary approaches." With their limited ability to capture the interconnections and interdependencies among the sub-systems, these tools and methods mostly provide a narrow and fractured perspective of the nexus, which is not in line with the goals of the nexus (ibid.).

Moreover, heavy reliance on quantitative approaches alone was found to be not sufficient (Albrecht et al., 2018): without the inclusion of contextual factors, the design of socially and politically feasible resource use (management) policies is problematic (Endo et al., 2015; Foran, 2015). In their study of nexus projects which link science and policy, Yung et al. (2019) found that combining modelling efforts with the approaches of qualitative futures thinking were helpful in including more contextual variables, especially relating to uncertainty. Although these methods can be challenging for both researchers as well as stakeholders, the authors acknowledged that this process led to a "more holistic framing of [the] problem and an acceptance of different types of uncertainties, beyond simple data gaps that are usually included in modelling" (ibid., 13–14).

Although the nexus approach explicitly states the need to understand the interlinkages among key nexus sectors for advancing WEF securities and resource sustainability through coherent policies, the existing body of research is generally inconclusive as to the exact magnitude of impacts that pursuing one security has on the others. It is also widely acknowledged that the development of methodologies for even the nearly accurate understanding of the physical interlinkages among the various different sector-specific activities across different contexts is still at a nascent stage. The neo-Malthusian premise and statistics about growing populations, growing energy and food demand, and growing water scarcity have resulted in a reductionist scientific approach to framing the problem as one of resource efficiency and resource optimisation in respective sectors (de Grenade et al., 2016; Wiegleb and Bruns, 2018; Yung et al., 2019). The underlying assumption of the approaches in most of the technical studies is that improved knowledge of the physical interlinkages and technical and managerial solutions would be sufficient to achieve the respective goals related to WEF securities. However, research on technology adoption in resource-based sectors has provided ample evidence that such adoption is mediated and constrained by institutions and governance mechanisms [for natural resource management (NRM) technologies in smallholder agriculture, see Shiferaw et al., 2009]. Further, the dynamics of power influence the spaces for participation and decision making for innovation and adoption in natural resource management (Cullen et al., 2014).

The dominant scientific discourse on WEF nexus takes a technical-managerial view of the problem and its solutions, which ignores the power relations and social inequalities as causes and consequences of actions (de Grenade et al., 2016; Wiegleb and Bruns, 2018). There is an increased recognition of the need to include the issues of governance and the political economy of the concerned policy fields (Allouche et al., 2014). Pahl-Wostl (2019) argues that WEF nexus is so far rooted in the scientific and technical rationalities for integration, accounting little for the "power constellations, political economy issues, and transaction costs and how they vary at and across different spatial scales."

In this article, we aim to close this gap by proposing a polycentricity approach to analysing WEF nexus interdependencies and their governance. Hence, the underlying question we pursue is: how can we analyse the governance of interdependencies in polycentric WEF nexus systems? After conceptualising a polycentric WEF nexus governance system, we present a generic adaptation of Ostrom (1990) Institutional Analysis and Development (IAD) framework and the concept of "networks of action situations" (McGinnis, 2011) and a suggestion how to include power for studying governance of WEF nexus. In the following: we first provide a brief review of the existing literature on WEF nexus governance and their shortcomings (**Section 2**); elaborate our conceptual framework of WEF nexus governance based on the polycentricity approach (**Section 3**); a brief discussion on suitable methods to operationalise the concept is then presented (**Section 4**), followed by conclusions (**Section 5**).

2 STUDIES OF WATER-ENERGY-FOOD NEXUS GOVERNANCE—A BRIEF REVIEW

Systematic analyses of the governance of the WEF nexus have been limited. In much of the nexus debate, an explicit focus on governance is missing (Al-Saidi and Elagib, 2017). In their review of governance approaches to the WEF nexus, Weitz et al. (2017) distinguished three perspectives, namely, technical (based on risk and security arguments); administrative (based on economic rationality); and political (based on the concerns of equity and power). The common proposition of all the perspectives, however, is that—in a given context—cross-sectoral coordination is required for managing the interlinkages and attaining WEF securities. Weitz et al. (2017) also argued that the technical and administrative perspectives do not explain why coordination does not occur, nor what the main barriers to coordination are.

If the interdependencies in the WEF nexus are to be addressed, both horizontal (across sectors) and vertical (across scales and levels) coordination are essential (Weitz et al., 2017; Pahl-Wostl, 2019). The primary objective of the WEF nexus governance analysis should be to unravel the conditions under which there is successful coordination among multiple interlinked decision-making centres. However, prior to the focus on coordination, it is important to identify and distinguish the relevant decision-making centres or action situations that are interlinked within the issues of water, energy and food. Various studies have employed different approaches to distinguish the interlinked decision situations related to the provision of food, energy and water security. Pahl-Wostl (2019) applied a combination of ecosystem services and actor network concepts and developed a typology of interactions among actors which depended on the type of ecosystem service of interest to the actors involved. The nature of interactions (the degree of directness or indirectness of interactions among involved actors) determined the type of governance mechanisms that might be effective in enhancing coordination. Further, Pahl-Wostl (2019) emphasised the importance of tele-connections among spatially remote actors without any established social relations through which they might influence each other and their interactions with nature, but who were connected through global trade. To this extent, a multi-level perspective was essential in order to address the governance gap in facilitating coordination among decision-making centres across levels and scales. Dombrowsky and Hensengerth (2018) found that regional organisations dealing with energy and river basins were instrumental in facilitating nexus governance in transboundary river projects through negotiating benefit-sharing arrangements and ensuring compliance with social and environmental safeguards.

Villamayor-Tomas et al. (2015) employ a novel combination of the value chain approach and the institutional analysis and development (IAD) framework (Ostrom, 2005) as well as the notion of the network of adjacent action situations (NAAS) (McGinnis, 2011) as an extension of the IAD to explore the biophysical and institutional interlinkages across different stages of production and consumption of food, energy and water resources. They select irrigation systems in four countries—Kenya, India, Spain and Germany—as cases of the WEF nexus that represent a close continuum of action situations along the value chain: water appropriation; electricity appropriation; and crop production. They found that the coordination problems identified in various different action situations of water and energy appropriations as well as the related crop-production choices were physically and institutionally interlinked. For example, in the Indian case, the technical and institutional solutions available for the coordination dilemmas relating to the quality of the electricity provided were found to be undermined by a series of institutional factors (subsidies on electricity, ineffective regulation of groundwater withdrawal and promotion of water-intensive crops) which were deeply rooted in the political economy of the country and the federal state (Kimmich, 2013). Further, the informal collusion of farmers and electricity service providers prevented investments to improve infrastructure for electricity generation and its maintenance. Such cross-sector path-dependencies were also found to hinder institutional reform of water and energy sectors in the Spanish case (Villamayor-Tomas et al., 2015).

A lack of recognition of the social embeddedness of interactions among actors was one of the key limitations of earlier approaches to governing water resources such as the Integrated Water Resources Management (IWRM). For this reason, Stein et al. (2018) followed a relational approach and analysed how existing social relationships shaped governance processes for WEF nexus interlinkages in the Upper Blue Nile basin in Ethiopia. They identified the network structure for nexus governance in Ethiopia as hierarchic, reinforcing the boundaries around spheres of political authority. Furthermore, they found that rather than sectoral boundaries, hierarchical relationships between actors at different governing levels, geographical locations and jurisdictions structured the interactions among WEF nexus actors (Stein et al., 2018).

WEF nexus literature likewise falls short on the knowledge of political and cognitive factors that determine policy change within the sectors (Weitz et al., 2017). The neglect of the inherently political nature of the WEF nexus problem by the dominant technical-administrative perspective of the nexus literature could possibly explain the dearth of knowledge on why incoherent policies and strategies persist. Failing to include the vertical interactions will provide only a limited understanding of the unintended consequences of the horizontally fragmented policies. The process of formulating and implementing sectoral policies relies explicitly on vertical coordination, and an analysis focusing on the vertical interplay of institutions can identify many of the factors that shape policy objectives the way they are, together with their effectiveness. Unravelling the institutional political factors behind incoherent sectoral policies and resulting trade-offs among WEF nexus goals require innovative research approaches.

Drawing on the research on integrative environmental governance, Weitz et al. (2017) suggested that coordination across WEF sectors and levels might be fostered through communicative, organisational, and procedural instruments. They further suggest that several attributes (principles) of governance—namely inclusiveness, transparency, accountability, empowerment of the weaker players, and access to information—also have a positive impact on coordination. The transformation of governance systems depends on the cognitive frames of the actors involved and "institutional learning processes" are crucial for such transformations (ibid., 171). Beyond cross-sectoral coordination, Daher et al. (2020) focus on convergence of perspectives between researchers and stakeholders on the interlinkages in the nexus in the San Antonio region of Texas. Although, they find only modest levels of communication among different groups, both researcher and stakeholder groups seem to agree on the importance of increased communication and information-sharing in addressing nexus challenges (Daher et al., 2020).

While most scholarship on the WEF nexus has focused on the biophysical interlinkages (material flows) between the differing sub-systems (Yung et al., 2019), social, political and institutional dimensions of the nexus have received comparatively little attention. Nevertheless, in recent years, more and more researchers are applying analytical approaches stemming mainly from environmental governance. Several recent case studies (e.g., Never and Stepping, 2018; Rodríguez-de-Francisco et al., 2019) focusing on WEF nexus issues in various geographical contexts have highlighted the embedded nature of the focal WEF nexus decision-making situation (of the particular research) in the horizontal (sectors) and vertical (levels) network of action situations with strong biophysical and institutional interlinkages. These case studies show that there would be value in an analytical approach that is more strongly theorised. There is a need to further enhance the existing conceptual and theoretical framework of WEF governance analysis by systematically analysing more cases in differing environmental, social, economic and political contexts as well as in the context of crucial global goals and conventions such as the 2030 Agenda. Furthermore, the role of important factors in achieving coordination—such as different forms of power influencing the interaction among decision-making centres—need to be better accounted for.

3 POLYCENTRIC VIEW OF WATER-ENERGY-FOOD GOVERNANCE

Polycentric governance started as a descriptive concept of Vincent Ostrom and his colleagues with an ontological function of describing the ways in which metropolitan areas organised themselves to provide public goods and services (Ostrom et al., 1961). What began as a descriptive label for an observed pattern of societal organisation turned into a theory of polycentricity or polycentric governance. There are normative and positive dimensions to it. In his treatment of the evolution of research on polycentricity, Thiel (2016) describes the concept, theory (normative and positive) and analytical framework as different constituents of the polycentricity approach. The concept has ontological, operationalising and sensitising functions. As defined/described by Ostrom et al. (1961), polycentric refers to

> . . . many centres of decision-making, which are formally independent of each other. Whether they actually function independently, or instead constitute an interdependent system of relations, is an empirical question in particular cases. To the extent that they take each other into account in competitive relationships, enter into various contractual and cooperative undertakings or have recourse to central mechanisms to resolve conflicts, the various political jurisdictions in a metropolitan area may function in a coherent manner with consistent and predictable patterns of interacting behaviour. To the extent that this is so, they may be said to function as a system (Ostrom et al., 1961, 831).

Normative polycentric governance theory makes "hypothetical, value-laden statements about ways in which societies organise themselves in order to comply with certain performance criteria that are considered desirable" (Thiel, 2016). If a study subscribes to the normative perspective, this would mean that a polycentric system of organisation would lead to WEF securities without compromising on the sustainability of natural resources. The analysis would then focus on the conditions that lead only to the emergence of a polycentric WEF governance system, which is assumed to be inherently effective in managing the interdependencies. This would then be analogous with the recommendations of the huge body of research conducted on the governance of local common pool resources which is implicitly based on the normative polycentric theory (Ostrom, 2005; Thiel et al., 2019). Positive polycentricity theory, on the other hand, "posits specific causes that help to explain governance structures, actors' behaviour and performance of governance" (Thiel, 2016). Therefore, using positive polycentricity theory would mean that we test the claims that the normative theory makes in terms of its performance besides testing its causal conditions.

Heikkila et al. (2018) call for a positive analytical perspective on polycentric governance systems for environmental governance. They mention that "only pure centralised or decentralised systems, which are ideal types and elusive in practice, would fall outside the polycentric space" (Heikkila et al., 2018). Measurement of features and variation across polycentric systems are affected by the binary view of polycentricity: whether a system is polycentric or not. Against this conception, polycentric systems exist in multiple designs and functional forms. They further identify an empirical bias in the scholarship of polycentric systems towards a focus on traditional common pool resources (CPRs) which therefore excludes the interactions across sectors from its analysis (Heikkila et al., 2018).

In this section, following the analytical perspective, we outline a conceptual framework for understanding the governance of WEF nexus and adapt the IAD framework and the concept of NAAS to provide a heuristic for analysing coordination in WEF nexus systems. Srigiri et al. (2021) illustrate the application of this conceptual framework to understand the factors affecting the effectiveness of coordination across sectors and levels to manage the nexus interlinkages in the lower Awash River Basin of Ethiopia. Similarly, Dombrowsky et al. (2022) use the framework to analyse natural resource governance in Jordan's Azraq basin in light of the 2030.

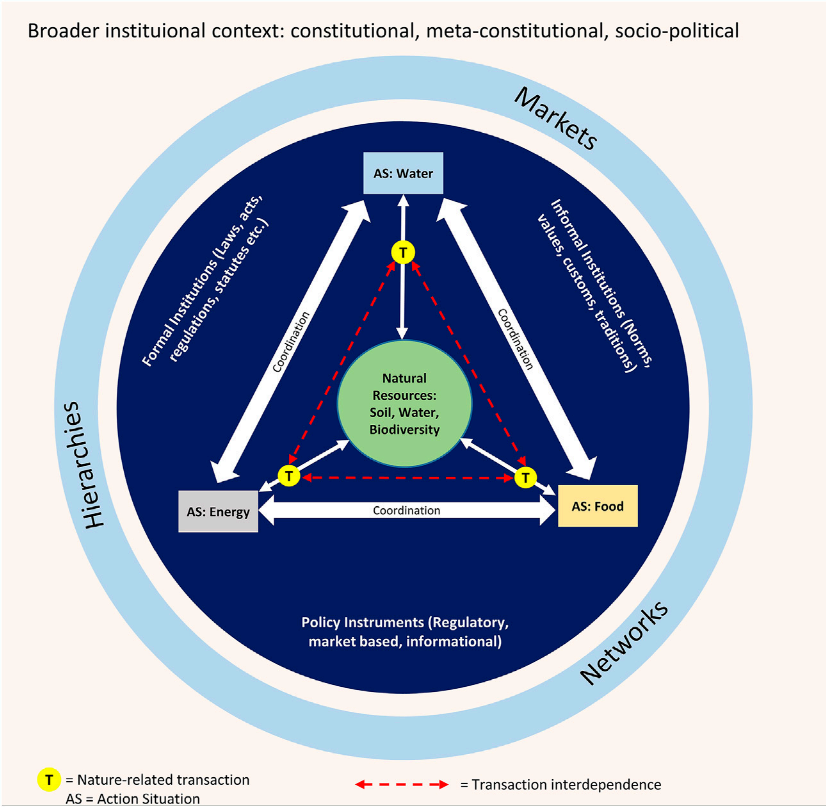

FIGURE 1 | Polycentric view of water-energy-food (WEF) nexus governance. Source: Authors.

For analysing WEF governance, we propose to start with an ontological description of different elements that are to be included in the analysis: namely, key decision-making units/centres; key resources of focus; institutions (formal and informal rules); possible modes of governance (hierarchies, markets, networks); and how these elements are related with each other. These elements form the constituents, or building blocks, of the analytical framework that could be applied as a heuristic to assess the performance of the various arrangements in the governance as observed in various empirical settings according to desirable performance/evaluative criteria. We believe that the provision of WEF securities is generally organised in different sectors with differing and sometimes overlapping sets of actors, who organise and make decisions in different, but interdependent, action situations on the use and management of natural resources, especially water, soil and biodiversity, for either independent or joint provision of water, food or energy. Although, these action situations are formally independent, their dependence on the same natural resources make them functionally interdependent. Thiel and Moser (2019) mention that, in the realms of management of water or other natural resources, functional interdependence means that governance and its performance are affected by a multitude of activities. These decision-making centres and action situations for water, energy and food provision are embedded in an overarching system of constitutional and meta-constitutional rules. **Figure 1** presents a description of polycentric arrangements of WEF nexus governance.

3.1 Common Pool Resources and Interdependence of Nature-related Transactions

Natural resources (especially water, soil and biodiversity) are at the core of the nexus on which the WEF securities depend. Water in particular is crucial for the production of food and energy, as well as for fulfilling the drinking and sanitation needs of humans. Similarly, soil and biodiversity are vital inputs for food production. Generating energy requires water and, in the process, can degrade biodiversity, water and soil resources if environmental and social safeguards are not adhered to. Attributes of natural resources play a very important role in understanding the use patterns of differing actors for different purposes (Ostrom, 1990). For instance, incentives for the appropriation of resource units are based on the attributes of rivalry and excludability of the resources. Water—be it surface or groundwater—is a classic "common pool" resource where high levels of rivalry exist, meaning that one actor's use diminishes the quantity or quality of the resource for another actor. At the same time, options for excludability are typically low. Hence, sustainable water extraction requires some institutions that increase excludability. Mentioned in the literature are several other attributes of resources—for instance, size, location, predictability, and so on—that play a crucial role in determining the type of institutions that are suitable for sustainable management and use of water with different degrees of effectiveness (Agrawal, 2003; Birner and Wittmer, 2004; Ostrom, 2005; Epstein et al., 2013).

The pursuit of WEF securities by actors in multiple, autonomous decision-making centres fundamentally involves biophysical transactions between the respective actors and natural resources for the production of water for consumption, food production or energy generation. Hagedorn (2008) considers “nature-based transactions” and the interdependence they create as crucial determinants of institutional and governance arrangements that emerge or are suitable to be designed. While the concept or the focus on transactions as a unit of analysis is borrowed from industrial organisation, originally defined by Williamson (1987), Hagedorn (2008, 360) defines nature-based transactions as “economically relevant processes by which goods and services, resources and amenities, damages and nuisances are allocated”. He posits that transactions of goods caused by decisions made by actors usually also impact other actors positively or negatively, although they are not involved in the decision (Hagedorn, 2015). He further argues that, if the focus of the normative governance framework is to identify and promote institutions and governance solutions to achieve sustainability, then the physical properties of the nature-related transactions play a determining role and need to be considered in the analysis. Actors are the causal connection between transactions and institutions. Therefore, to understand the interdependence, it is important to study both the physical as well as social interdependence between actors or organisations (Hagedorn, 2015).

When the transaction of one actor affects another actor negatively, the latter actor is likely to perceive the interdependence and enter into negotiations with the actor initiating the transaction. These negotiations may then lead to the design or changing of certain rules. This means that the need for coordination among actors in interdependent action situations may arise as a result of the transaction interdependence. From a New Institutional Economics perspective, Williamson (1979) argues that complex recurring transactions require long-term relations between identified individuals. In other words, actors are more likely to engage in institution building within a hierarchical organisation rather than in an “anonymous market”. He further suggests that “governance structures” are needed to “attenuate opportunism” and infuse confidence in the economic transactions among self-interested actors. However, Granovetter (1985) argues that all behaviour—including economic transactions (within and beyond organisations)—are embedded in social relations (networks). In other words, the structures of coordination in a governance system are embedded in a broader social, political, and cultural context and their effectiveness depends on such a context.

3.2 Networks of Water-Energy-Food Action Situations

In order to understand the nature of polycentricity in WEF governance, it is necessary to investigate the context under which the actors make decisions and enter into several transactions in generating WEF securities. **Figure 1** provides a simplistic presentation of three action situations for food, energy and water provision, which in reality entail several interdependent action situations. Hence, we adapt the Institutional Analysis and Development (IAD) framework developed by Ostrom (1990), which is one of the most widely used analytical framework for studying polycentric governance systems. Thiel (2016) views the IAD as a framework that operationalises polycentric governance theory through its focus on self-organisation. Self-organisation is one of the possible organisational forms in polycentric governance systems.

The analytical framework has three broad components, which further entail various sub-components. They are—1) action situations and their networks across different levels; 2) exogenous variables, providing the biophysical, socio-economic and institutional context for action situations; and 3) outcomes, which can be operational or institutional in nature and refer to the wellbeing of actors involved, their access to key resources and to the sustainability of natural resources. A further important component of the framework, which stands out of the rest, is the “evaluative criteria” by which the observed outcomes and the processes that lead to outcomes are evaluated (**Figure 2**).

An action situation in the IAD framework is “an analytical concept that enables the analyst to isolate the immediate structure affecting a process of interest to the analyst for the purpose of explaining regularities in human actions and results. . .” (Ostrom, 1990, 11). It is a situation in which two or more actors participate by taking specific positions and choosing from a set of possible actions, that lead to a particular outcome, which in turn have different pay offs for each participant in the situation. Actors may be individuals or an organized entity of individuals who participate in a given action situations. Participants act upon information available to them about costs and benefits of actions, outcomes and their individual payoffs that depend on the rules for distribution of costs and benefits (Ostrom, 2005). The information about the actions and outcomes and the rules that determine the individual payoffs in a given action situation may be generated or devised in a different action situation, which may have same, overlapping or different participants depending on the type of institutional arrangement in place. For example, different users appropriate water from a resource system in one action situation, subject to the rules designed by the same users by forming a water user association (WUA) in a functioning decentralised self-governance system. In other cases, where the authority to design rules of appropriation or management

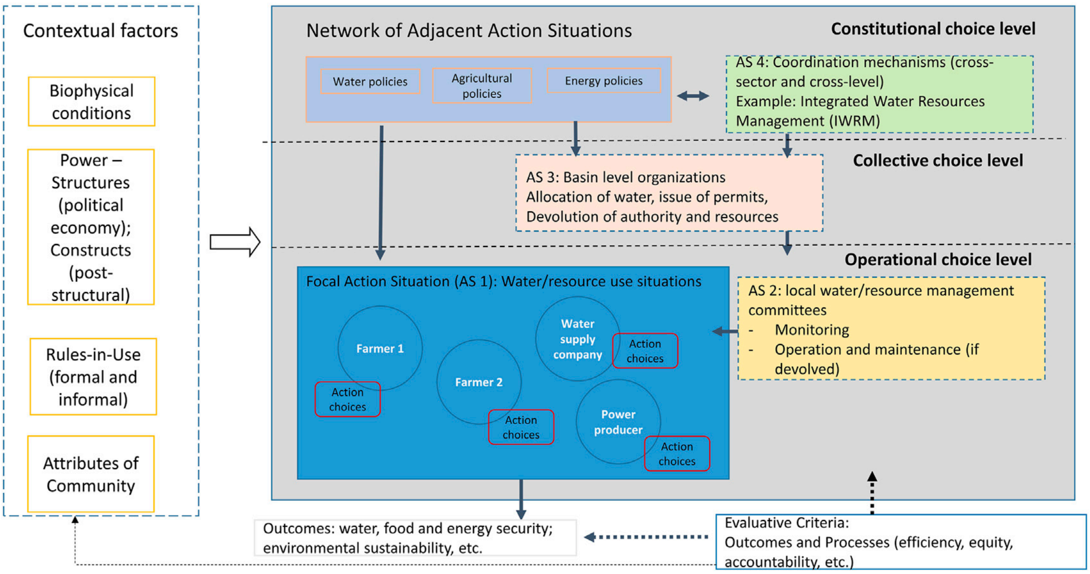

FIGURE 2 | Networks of adjacent action situations in provision of water, energy and food (WEF) securities. Source: Authors (based on Ostrom, 1990; Clement, 2010; McGinnis, 2011).

is not devolved to local communities, different set of actors, mostly from the governmental authorities participate in the action situation for designing rules.

McGinnis (2011) further elaborates the concept of action situations in the IAD framework by stating that various functions of polycentric governance such as production, provision, financing, coordination and dispute resolutions, all occur in distinct action situations adjacent to each other. He states that "an action situation Xi is adjacent to Y if the outcome of Xi directly influences the value of one or more of the working components of Y" (McGinnis, 2011). These action situations may be spread across different action arenas or conceptual levels of analysis (Ostrom, 2005, 58–62): 1) operational choice level, wherein the outcomes of action situations are more tangible, related to wellbeing of actors involved and natural resource conditions, 2) collective choice level, wherein the outcomes of action situations are institutions or rules that define the set of action choices at operational choice level, and 3) constitutional choice level, wherein the action situations result in procedures for processes or action situations at collective choice level. The outcomes of actions at this level also legitimize the participation of actors (individuals or organizations) in different action situations at collective and operational choice levels.

Actors in the action situations are influenced by the contextual factors that include biophysical, social, political and institutional conditions. Biophysical context of an action situation includes conditions of resources (land and water), their abundance, scarcity, temporal and spatial distribution, availability and access to different actors, particularly relevant to the action situations at the operational choice level. It also includes climatic conditions as well as their short and long-term variability and change. Further, the characteristics of resources explained in Section 3.1 determine the actions of actors in different situations.

Rules-in-use impose constraints on actions of actors and their mutual interactions (North, 1993). They include both formal rules (laws, regulations, statutes, etc.) and informal rules (societal norms, customs, values, beliefs etc.) and their enforcement characteristics. It is important to understand both formal and informal rules-in-use to explain the behaviour of actors in different action situations and their outcomes. Further, Ostrom (2005) identifies seven different types of rules-in-use, which correspond to different working components of the action situation. The boundary, position, choice, information, aggregation, payoff and scope rules emerge as outcomes of interactions in distinct action situations in different arenas or choice levels of analysis (ibid.).

Community attributes such as heterogeneity, size, and level of trust determine mainly the capacity to coordinate and solve social dilemmas in different action situations, especially relevant in the operational choice arena (Agrawal, 2003).

Actors within an action situation or across action situations through their actions engage in patterns of interaction with each other. Patterns of interactions within different action situations generate joint (intermediate) outcomes. They either feed into other action situations as rules, resources and information forming the feedback loops within the network of action situations. The outcomes of a resource governance system as a whole are a combined result of different intermediate outcomes of independent action situations and as affected by the contextual factors which are external to the network of action situations. Such outcomes can be both material and institutional in nature. Material outcomes may include changes in the social or economic situation of involved actors or changes in the condition of natural resources used or managed in different action situations. Institutional outcomes include changed perceptions, values and beliefs resulting from patterns of interaction, which are further internalised by participating actors in the action situations. The institutional outcomes occur over longer time periods and therefore cannot be easily observed or measured.

Further, structures and relations of power, in which the actors in different action situations are embedded in, also constrain the choices of certain actors and determine the type of interactions between actors and their outcomes. We describe different forms of power and how they can be considered in the analysis of governance under **Section 3.4**.

In a system of nested action situations, it is important to choose a focal action situation, considered critical for the intended analysis (McGinnis, 2011). Most studies focusing on the management of common pool resources analyse behaviour of actors pertaining to use and management of natural resources, and therefore focus primarily on action situations at the operational choice level, which yield tangible outcomes.

3.3 Coordination in a Polycentric Water-Energy-Food System: Governance Modes

Scholarship relating to the WEF nexus is quite unanimous in its calls for more and effective coordination across sectors and multiple levels for governance of WEF nexus interlinkages (Pahl-Wostl, 2019). As water, energy and food are interdependent policy issues that are dealt with and are affected by actors across different policy domains, coordination is required to achieve coherence along the entire policy process (Hedlund et al., 2021). Although coordination is sometimes used interchangeably with other related terms such as cooperation in literature, we understand coordination as "the extent to which organizations attempt to ensure that their activities take into account those of other organizations" (Hall et al., 1977: 459, quoted in Bouckaert et al., 2010: 15). It is an alignment of tasks and efforts of organisations across policy sectors, which could be either forced or voluntary (Bouckaert et al., 2010). As explained below, we consider coordination as the overriding term and cooperation, competition and coercion may be principles based on which it is achieved. Polycentric systems are often associated with effective coordination in combination with the decentralisation of power. Pahl-Wostl and Knieper (2014), for example, define polycentric governance systems as "multiple centres of authority and distribution of power along with effective coordination structures." Based on the degree of centralisation of power and the degree of coordination, they categorise governance regimes into four categories: centralised-coordinated; centralised rent-seeking; fragmented; and polycentric. They then associate polycentric systems with positive outcomes, namely, increased resilience against shocks and as supporting experimentation and learning (Pahl-Wostl and Knieper, 2014). However, from a positive analytic conceptualisation, we define polycentric systems more liberally as being multiple decision-making centres with varying levels of authority and access to power resources and a variety of (coordination structure) interactions, which may, or may not, be effective and efficient in achieving social, ecological and economic outcomes.

There may be a variety of arrangements or modes of governance, which lead to coordination among decision-making centres. Governance modes are organisational solutions aimed at making the institutions or rules effective (Hagedorn, 2015) in realising different purposes of governance. The purpose of their design is to facilitate coordination of interactions among constituent autonomous decision centres. Public administration literature suggests that different governance modes such as networks, markets and hierarchies exist (Bouckaert et al., 2010) that are based on the principles of cooperation, competition or coercion (**Figure 1**).

In a hierarchical mode, a central authority may coercively devise and enforce rules for coordination. Cooperation can be understood as interaction where the agreed upon rules are jointly designed and enforced by the constituent decision-making centres to achieve shared goals. Such interaction opens up the space of governance to non-government actors who together with other actors may work together towards achieving shared goals (Koontz and Garrick, 2019). Another important contractual relationship through which different decision centres in a polycentric system take each other into account is competition. It is also argued by economic liberalists as an efficient form of interaction for producing public goods and services (in this case, water, energy and food) in a polycentric system as it results in the emergence of markets (Koontz and Garrick, 2019).

In order to internalise the externalities of nature-related transactions, specific policy instruments are required. Further, policy instruments require suitable governance modes for their effective implementation. Which modes of governance promote coordination for internalising the externality costs effectively depends on the properties of the transactions (as discussed in the earlier section) as well as on meta-institutions which create the enabling environment for actors at operational and collective choice levels to make rules. The choice of governance mode also depends on the type of goods and how the property rights to the resources and their ecosystem services are defined. In the case of high rivalry and a lack of excludability, a market mode of governance may not be a feasible option, but other forms of governance such as networks or hierarchy may work.

Pahl-Wostl (2019) argues that a combination of different governance modes—collaborative networks, market-based approaches and regulatory frameworks—is essential for achieving coordination among different decision-making centres. Hybrid governance forms, combining two or more governance modes, are purposefully designed structures and may be manifested in different types of policy instruments that are used to achieve a policy goal (Pahl-Wostl et al., 2020). Especially in irrigation management, combining hierarchical irrigation system governance with participatory irrigation management (Newig et al., 2019) or farmer-managed irrigation system (FMIS) emerged as an "institutional panacea" in the 1990s (Meinzen-Dick, 2007; Gandhi et al., 2020). Further, Leininger et al. (2018) emphasise the role of combining various different governance modes for governing the interlinkages among WEF-related SDGs as the following three cases illustrate. A combination of voluntary agreements between water supply companies and formal regulations (namely, the German Drinking Water Directive and EU Nitrate Directive) were initially successful in adopting sustainable production practices and reducing nitrate leaching (Richerzhagen and Scheumann, 2016). Later, a parallel promotion by the European Union and Germany for biomass and renewable energies offset these positive effects. Similarly, a market-based mechanism that was implemented in the Hidrasogamoso hydropower plant in Columbia was only sufficient in compensating the upstream farmers for conservation of biodiversity as well as preventing the sedimentation of the reservoir. On the other hand, the mechanism did not compensate the losses of the downstream water users who had less water available for food production (Rodríguez-de-Francisco et al., 2019). Therefore, a hierarchical arrangement to ensure that the principle of "leave no one behind" (LNOB) would need to be integrated into the governance of water resources for energy and food production in the Columbian case. Similar observations were made pertaining to the need for the hierarchical mode for sequentially reforming the water and energy sectors in order to provide the right incentives for private actors to participate in wastewater treatment in India (Never and Stepping, 2018). Hence, it is clear from the above examples that no single mode of governance will be sufficient to achieve all the three securities of the nexus and not exclude any interest groups from the benefits.

Policy instruments to facilitate or constrain an action towards achieving a desirable outcome—in this case one of the WEF securities—need to be evaluated not only for their impact on the provision of the intended collective good but also in how far they impact the provision of other goods of interest. Going by the famous Tinbergen's (Tinbergen, 1952) rule that each policy target should be matched with one tool, there is a need to check for the interactive effects among policy goals, among tools or policy instruments that may belong to different sectors or levels of the government (Del Rio and Howlett, 2013). Del Rio and Howlett (Del Rio and Howlett) further note that it is difficult to achieve horizontal and vertical coordination at the same time. This is because of the existence of different goals at different levels of administration and is moreover a result of the non-uniform distribution of costs and benefits across levels, which creates "winners and losers" for each instrument. The different logics of policy instruments and different principles underlying the different modes of governance may sometimes lead to conflicts instead of synergies making a particular combination incompatible and thereby inefficient in achieving the policy objectives (Pahl-Wostl et al., 2020). For example, in the Indian irrigation systems, Mollinga et al. (2007) noticed that reluctance on the part of central and state agencies to devolve power to water user associations (WUAs) did not provide incentives for the participation of water users and that this explained the varied and limited success of the particular combination of hierarchy and network modes of governance. For this reason, the context-based assessment of possible interactions both within and beyond policy mixes, based on the underlying principles, is crucial for their effectiveness in achieving the intended policy goals.

Koontz and Garrick (2019) further describe three factors that provide incentives for engaging in different interactions between each other: authority, information and resources.

Authority defines the limitations of different decision centres allowing them or forbidding them to take particular actions or entering or exiting particular interactions with each other. In the public sector, authority is usually assigned or devolved by a higher constitutional authority. Devolution of authority is an essential element of various decentralisation strategies pursued in different parts of the world, involving both responsibility as well as constitutionally backed power to make decisions regarding production as well as social, political and legal transactions with respect to a specified policy area and jurisdiction. Effective decentralisation of authority may guarantee the formal autonomy of a decision-making centre, which is an important attribute of polycentric systems of governance. The distribution of authority among decision-making centres across different levels is crucial for facilitation of competitive and cooperative interactions. Which interactions emerge further depend on other conditions of access to information and resources.

Information on the costs and benefits of alternative production mechanisms for public goods, externalities, and transaction costs are crucial if actors in different action situations are to decide on alternatives of production or interaction with other actors. Information on the roles and responsibilities of the various different actors is helpful in increasing the accountability and transparency of the governance process.

Access to financial, human and natural resources is vital to carrying out the assigned or agreed upon roles and responsibilities in generating public goods or monitoring the provision of goods and services. Distribution of access to key resources also defines the power relations among actors in a governance system. Actors with a shared mandate may enter into cooperative relationships of sharing resources and complementing each other in achieving shared goals.

The types of interactions or coordination mechanisms that emerge in a given context depend on the distribution of authority, information and resources across decision centres. There are opportunities for all three kinds of interactions, competition, cooperation and coercion to occur in a system where multiple centres exist under a common set of overarching rules (Koontz and Garrick, 2019). How the three vital elements are distributed among differing actors and decision centres is further contingent on the social, political and cultural contexts.

3.4 Analysing Power in Governance Systems

Social structures, or relationships in which the interactions among actors are embedded, provide some insights into the opportunities and constraints faced by actors in making their choices between possible interactions or coordination with other actors (Stein et al., 2018). Stein et al. (2018) assert that three forms of embeddedness create conditions for coordination and cooperation through multiple network mechanisms at different network levels—namely positional, relational and structural. While a network approach can "unpack" power relations to some extent by identifying powerful actors in terms of their centrality, it is not sufficient to explain the cultural, historical and political context crucial to the understanding of the meanings and dynamics of social networks. "Power and justice" affect interactions, outcomes and performance in a governance system. In consequence, political dimensions need to be better integrated: Skelcher (2005), for instance, suggests integrating polycentricity theory with the theory of democracy as one useful approach.

The IAD framework has been criticised for the fact that the decisions of actors and their outcomes are often explained with recourse to rules and that this often ignores the role played by power dynamics in shaping institutions (Cleaver, 2000; Clement, 2010). Although the IAD provides a solid basis for multi-level analysis through its conceptualisation of nested action arenas and governance levels, it does not sufficiently capture the influence of intra- and inter-level power distribution on institutional design and effectiveness (Clement, 2010). The effects of power asymmetries, which are more widespread in the less industrialised societies, are spread across multiple and interlinked social and political arenas (Kashwan, 2016).

Increasing efforts have been made to address this gap by integrating the approaches of political ecology to understand the critical role of power in environmental governance into the institutional analytical approaches. The broad conceptualisation of institutions as "prescriptions that humans use to organize all forms of repetitive and structured interactions including those within families, neighbourhoods, markets, firms, sports leagues, churches, private associations, and governments at all scales" (Ostrom, 2005) allows for the integration of power relations as one of the conditioning institutional processes leading to particular political outcomes (Clement, 2010; Bennett et al., 2018). Bennett et al. (2018) develop a relational typology based on the antecedent and consequent relation between power and institutions as well as political economic and post-structuralist conceptualisations of power that are prevalent in political ecology approaches. The political economic "power structures" such as capitalism, class, gender, and so on are based on the premise that power resides in stable societal structures that determine control over, and access to resources. In contrast, post-structural "power constructs," such as discourses, narratives, power/knowledge, subjectivities etcetera, influence individuals and groups in their operations as well as shaping the reality (for instance, environmental problems) (Bennett et al., 2018). The authors further mention that post-structural power constructs provide a methodological approach to studying how the social norms and internal values emerge and change. Based on the relational typology developed by Bennett et al. (2018) for understanding the relationships between power and institutions, we can formulate a range of research questions about relationships between operationalisable concepts of institutions, power structures and power constructs.

4 METHODOLOGICAL STEPS TO ANALYSE POLYCENTRIC WATER-ENERGY-FOOD SYSTEMS

A wide variety of methods—namely small-N case studies; comparative field-based research; meta-analysis; laboratory and field experiments; agent-based modelling—have been used in combination with the IAD framework (Poteete et al., 2010). Almost all of the studies focused on single action situations and single collective/public good of interest.

Following the enhancement of the IAD framework to include the adjacent action situations along with the focal action situation (McGinnis, 2011), a few authors have started to explore new combinations of methods to analyse the interactions among different action situations and thereby offer a more complete explanation of the choices and outcomes of the focal action situation. Kimmich (2013) employs a combination of NAAS and Ecology of Games (EG) frameworks to understand the coordination dilemmas of the interlinked energy and water systems in India. Villamayor-Tomas et al. (2015) employ a combination of NAAS and value chain frameworks to understand similar interlinkages in Spain. Both studies relied on quantitative and qualitative data obtained from primary and secondary sources. Both Ecology of Games and NAAS approaches go beyond the normative focus about the virtues of polycentric governance and mere descriptions of action situations (in NAAS) or policy games (in Ecology of Games). They are helpful in generating empirically testable hypotheses about the structure of the game or action situations, analysing the drivers of individual behaviour and institutional change and showing how these lead to policy outputs and outcomes (Lubell, 2013).

One of the initial and crucial tasks in a WEF nexus study is to identify the relevant focal action situation and adjacent action situations. This essentially depends on the research question and the WEF issues that the research project is focusing on. There can be numerous adjacent action situations surrounding the focal action situation. However, the selection should depend on the theoretical proposition and the empirical knowledge (Kimmich, 2013) gained through exploratory field research approaches such as secondary data, review of the literature, and interviews with key actors.

Stein et al. (2018) use the concept of "problemshed and issue network," originally proposed by Mollinga et al. (2007) in selecting a unit of analysis. This concept moves beyond a pre-defined geographical unit of analysis (such as a watershed) or a sectoral focus (for instance, water) to include a broad set of issues that are linked to the context of a problem. "Problemshed" is framed through an iterative process by the researcher, or co-constructed with stakeholders. The specific issues of WEF nexus interlinkages as a framework can guide in framing the problemshed. In the understanding of this paper, a problemshed would entail networks of adjacent action situations.

Network theory and analysis is increasingly being used to disentangle the complex interdependencies in polycentric systems. Social network analysis (SNA) is a tool to understand the characteristics or structure of a network by identifying the actors involved in a network and their relationships. This approach helps to understand how social relationships shape governance processes and provide opportunities and constraints for addressing complex and interconnected sustainability challenges (Stein et al., 2018). The centrality of different actors and actor groups is determined and influential actors with a bridging position are identified. Whether the understanding could be extended to the functionality of the networks is a question that is not fully explored in current studies (Lubell, 2013). Relational data generated from the network survey can be transferred into adjacency matrices representing various issue networks identified on the basis of the concept of problemshed and issue networks (Mollinga et al., 2007) mentioned above.

SNA relies on primary data collected from actors who are participants in selected action situations through a structured network survey questionnaire, which focuses on the positional, relational and structural attributes of the network embeddedness. Alternatively, "NetMap" is a method to identify the action situation network following a participatory approach (Schiffer and Hauck, 2010).

Going beyond the quantitative SNA, semi-structured interviews with actors participating in action situations are useful to understand the considerations behind the decisions of actors as well as the structure of the action situation. Further, focus groups with groups of actors within an action situation is a useful technique to gather data on group dynamics and elicit particular kinds of historical or recent data, which are often found to be more reliable if they emerge out of a discussion among actors with similar interests.

5 CONCLUSION

The majority of the scholarship on the WEF nexus focuses on substantiating the biophysical interlinkages among the related sectors of water, food and energy. These help in understanding the magnitude of the problem in different contexts and in strengthening the case for integrated governance of the WEF systems. However, social, political and institutional interlinkages, crucial for understanding and evolving an integrated governance approach, have received less attention. This is the result of the dominant technical-managerial view of the WEF nexus problem. The recent surge in analyses of the WEF nexus using the analytical approaches of environmental governance has emphasised the need for more and effective horizontal (cross-sectoral) and vertical (cross-level) coordination in order to avoid trade-offs and to achieve synergies in realising WEF securities. However, prior literature falls short of explaining the conditions under which such coordination occurs.

In our effort to further the WEF nexus governance research, we have conceptualised WEF nexus governance as a polycentric system. Further, we have argued that analysis of a polycentric WEF nexus governance system would help, first, to understand the relations and interactions among the constituent decision centres which we have conceptualised as networked adjacent action situations; and, subsequently, to investigate the conditions under which different types of interactions emerge among the decision centres. We then proposed a conceptual framework covering various components of WEF governance systems and their logical interrelations. The conceptual framework highlighted the need for coordination arising out of the interdependence of WEF-related transactions by actors in various different interlinked action situations.

Various forms of coordination—namely cooperation, coercion and competition to manage the interdependencies in WEF nexus—are achieved through various means. Which type of interactions different decision centres engage in to coordinate their transactions is dependent on the way authority, information and resources are distributed among the decision centres. It was further argued that WEF nexus governance requires a combination of differing coordination mechanisms or modes in order to manage the cross-sector and cross-scale interlinkages. The coordination mechanisms of hierarchies, markets and cooperation are further embedded in the social structure or relationships, which facilitate or constrain coordination.

The proposed analytical framework based on the concept of network of adjacent action situations (an extension of the IAD framework) has the potential to operationalise the analysis of polycentric WEF nexus governance systems. The analytical framework provides a heuristic for formulating research questions relevant to the context and hypotheses related to conditions affecting the action situation and the interactions among action situations. Further, integrating the approaches from political ecology to understand the role of power structures and power constructs will support the inquiry into how power relations shape, and are shaped by, rules-in-use at various levels. The framework also allows one to assess the performance of the governance system based on outcome and process criteria defined in the respective context and the indicators suggested by theory.

Methodological innovation is called for in operationalising the analysis of polycentric governance systems in the context of WEF nexus. Instead of delineating action situations based on sectoral boundaries, we propose the application of the "problemshed" concept so that the analysis can be focused on the actual issues facing the coordination problem and so that the coordination can be assessed for its conditions and performance in solving the problem. A combination of approaches that study social networks as well as institutions, actors, and resource characteristics may complement each other in providing a holistic understanding of how a specific situation of WEF nexus governance is organised and performs.

Finally, it is important to note that issues and problems of WEF nexus interdependencies vary across different biophysical, political and economic contexts. For example, not all the elements of the nexus may be relevant in all contexts. In some river basins, energy may be generated entirely from other sources than water and in other contexts, water in agricultural sector may be prioritized for non-food crops, for which there exists a comparative advantage and importing food may be cheaper than domestic production. Moving beyond the given nexus elements of water, energy and food and conceptualising context relevant nexuses in different case studies may be one option. Common reference point for comparison would then be a resource management unit such as watershed, or river basin or sub-basin.

AUTHOR CONTRIBUTIONS

SS and ID jointly conceived the idea for the paper. SS conducted the literature review on WEF nexus governance and elaborated the conceptual framework in **Sections 3.1**, **3.2**, **3.4**. SS and ID jointly wrote the **Section 3.3** on coordination and governance modes. SS wrote the **Section 4** on methodological steps. SS and ID together jointly wrote the conclusion.

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