Chapter 5

ENVIRONMENTAL SUSTAINABILITY
The Intersection of Agrifood Systems with Ecosystem Health

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Key messages

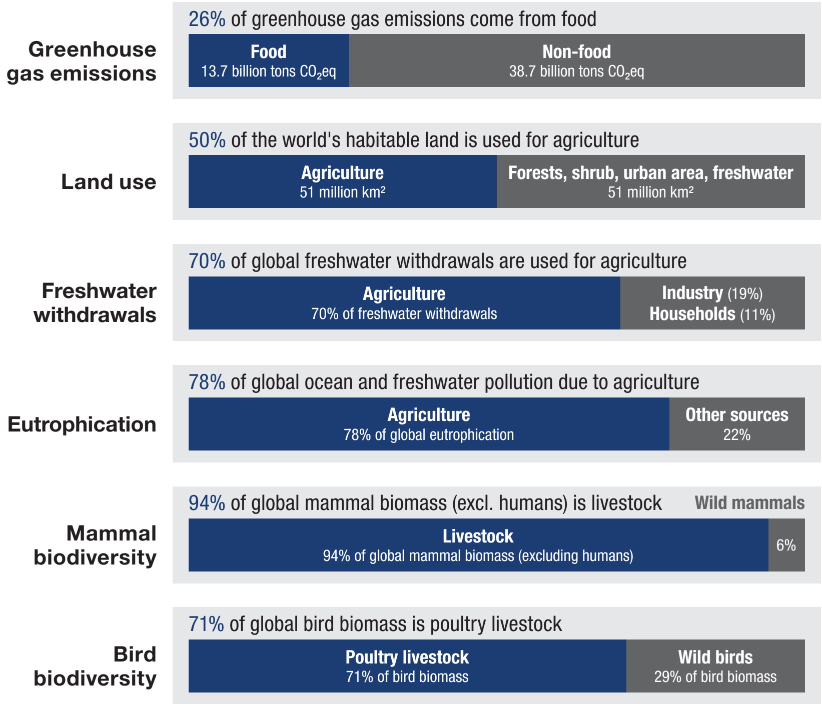
- Unsustainable food systems are both a cause and consequence of environmental degradation. Despite global attention to climate change, biodiversity loss, and natural resource degradation, progress in understanding and addressing the problem has been slow at best.
- Over the last 50 years, research has evolved amid growing recognition of environmental degradation, the importance of ecosystem services and biodiversity, and the role of property rights, institutions, and governance.
- In response, researchers have offered insights on balancing agricultural productivity with environmental sustainability, as well as the role of governance and collaborative management.
- Innovative approaches, such as behavior-based methods that use games to simulate resource use decisions, have also catalyzed community action.
- More recent systems approaches aid in understanding complex relationships and can support integrated landscape approaches for development and conservation.

Looking to the future, research for sustainability should:

- **Strengthen systems thinking within and across food and linked systems.** Increasing sustainability requires considering not only food value chains but also diets, health, and energy systems, among others, in designing policies.
- **Commit to transdisciplinary research processes.** Research must actively include stakeholders who manage resources, such as farmers, in identifying and assessing interventions.
- **Strengthen political economy and policy process research.** Achieving wider implementation of tested interventions will require research on obstacles to adopting policies and practices for sustainability.
- **Apply an environmental justice lens in agrifood systems research.** Research on women's empowerment, energy use, and water insecurity highlights the critical importance of strengthening outcomes for those most disenfranchised by environmental degradation.
- **Improve the incorporation of feedback in systems models.** Better accounting for feedback loops within current models, such as the impacts of food systems on climate, is essential for understanding and acting on a range of environment–agrifood system interactions.
- **Accelerate game-changing innovations.** Emerging technologies can revolutionize how food is grown, but research on innovation constraints is needed to inform policies that support adoption of more sustainable technologies and practices at scale.

Climate change and biodiversity loss are arguably the greatest environmental challenges facing humanity today, and unsustainable agrifood systems are both a key cause and consequence of this rampant environmental degradation. Agrifood systems are directly linked to climate change, freshwater depletion and pollution, deforestation, and soil degradation and desertification (Figure 5.1). Following the 1992 Earth Summit, which drew global attention to unsustainable resource use, three of these critical challenges—biodiversity loss, climate change, and desertification—were taken up by United Nations conventions that established mutually agreed-upon goals and periodic global meetings to review progress. However, improvements in environmental sustainability have been uneven at best, with continued rapid degradation that poses a growing risk to all life on Earth. This chapter

FIGURE 5.1 The environmental impacts of agrifood production



Source: Ritchie et al. (2022), based on data from Poore and Nemecek (2018); FAO (2011); and Bar-On et al. (2018).
Note: CO_2eq = carbon dioxide equivalent; km = kilometers.

reviews how key environmental challenges intersect with agrifood systems and describes research contributions toward understanding and addressing these challenges over the past 50 years, and then explores some future directions for environmental sustainability research.

The beginnings: The Green Revolution

Agricultural productivity and overall food security increased dramatically with Green Revolution technologies and practices introduced in the 1960s and 1970s. These achievements were accompanied by rapid increases in environmental degradation, greater dependence on inputs, and progressive loss of social-ecological resilience as a result of more expansive, genetically uniform monocultures that relied on greater use of chemical inputs and water control (Conway and Barbie 1988; Pingali 2012). Environmental impacts were neglected or, when acknowledged, were accepted as a necessary byproduct, to be mitigated as feasible. While these environmental externalities were neglected, the increased agricultural productivity did reduce the need to convert additional pasture and forest lands to agricultural production, conserving several million hectares of land (Stevenson et al. 2013). Yield improvements—and the associated land sparing—are recognized as an implicit benefit to environmental sustainability.

CGIAR contributed substantially to the technical advances of the Green Revolution (Evenson and Gollin 2003; Pingali 2012), and CGIAR research continues to be closely identified with its tenets, even as the organization has broadened its scope to food systems research (CGIAR Systems Organization 2021). When IFPRI was established in 1975 and then joined CGIAR in 1980, the benefits of the Green Revolution were being reaped largely in the form of lower levels of hunger due to increased yields of key staple crops (see Chapter 3).

IFPRI's initial remit was (1) to research the enabling policy environment for Green Revolution technologies and practices that would strengthen their impact on food security, (2) to assess trends and factors that could adversely affect the world food situation, and (3) to assess linkages between agricultural and broader economic development (see Chapter 17, Box 17.1) (Farrer 2000).

Even though IFPRI's mandate did not originally include environmental sustainability, the Institute did early on examine broader impacts of incentives, trade, and other policies and institutions affecting agrifood systems. In particular, researchers at IFPRI and elsewhere began to analyze the impacts of subsidies and other policy measures on agricultural productivity and the environment. Key environmental challenges included imbalanced use of fertilizers and pesticides as well as growing water scarcity. Research suggested changes that would better balance productivity with environmental goals, particularly for the intensively cultivated rice and wheat areas of Asia. Examples include research on irrigation water use in the Philippines (Rosegrant 1985), on the sustainability of irrigation (Svendsen 1987), on fertilizer subsidies in Bangladesh (Ahmed 1987), and on food subsidies in Mexico (Lustig 1986).

Policies and institutions for environmental sustainability under Agenda 21

As environmental impacts from human development worsened, including from agricultural intensification, the United Nations organized the Earth Summit in Rio de Janeiro in 1992, with the goal of putting sustainable development on the global policy agenda. The resulting Agenda 21 aimed to increase food production, reduce poverty levels, and improve the state of critical ecosystems (Desai and Ringler 2013). Another outcome of the Earth Summit was the establishment of three conventions to address particularly vexing environmental challenges, namely climate change, biodiversity loss, and desertification.

Just ahead of the Earth Summit, the second external program review of IFPRI had recommended, among other things, a research focus on environmental policies (CGIAR TAC 1991). The report noted that national agricultural policies tended to favor short-term food production over longer-term natural resource conservation, and that economic assessments of environmental externalities were lacking. Advances in environmental research linked to agrifood systems in the 1990s included work on water systems, soil health, tropical forests, and pest management.

Research on the future of water and other environmental resources

Recognition of the fundamental role of water in agricultural production systems, including in transforming low-production systems into high-production systems, led to substantial new research on optimizing agricultural water use in the context of hydrological systems, with attention to the role of institutions and governance arrangements as well as foresight studies (Meinzen-Dick 2014; Rosegrant et al. 2000, 2002). With water quantity quasi-finite and most withdrawn freshwater resources used in agriculture, understanding water futures and their implications for food security garnered growing attention. In 2000, the *World Water Vision* report (Cosgrove and Rijsberman 2000) described a global water crisis and called for systemic shifts and behavioral changes toward making water "everybody's business." This report was followed by *Water for Food, Water for Life: Comprehensive Assessment of Water Management in Agriculture*, led by the International Water Management Institute, which undertook a deep exploration of agricultural water futures (Molden 2007). A recent re-assessment of this work (Seijger et al. 2025) noted that most of its projected water productivity gains were too optimistic and had not materialized. This was mainly because expected photosynthesis breakthroughs had not occurred, and other interventions to address water scarcity had not taken place. Instead, agricultural production areas were expanded, freshwater resources dwindled, and environmental degradation continued.

Another milestone was the Millennium Ecosystem Assessment (MEA 2005), a scientific assessment of the world's ecosystems and their services that provides the basis for conserving and using ecosystems sustainably. The report systemized ecosystem services, which include provisioning services, such as food and water; regulating services, such as climate or flood regulation; supporting services, such as soil formation; and cultural services. More than 1,300 experts contributed to this report, including IFPRI and many other CGIAR researchers.

All these assessments highlighted the need for policies and institutions designed to address the environmental externalities of agricultural production. In this context, IFPRI researchers introduced some of the first global modeling tools to examine the impact of alternative agricultural futures and underlying water needs and key ecosystem services (Ringler et al. 2010; Rosegrant and Cai 2002; Rosegrant and Ringler 1999), such as food and water security, and related trade-offs across development goals. This work provided the natural resource basis for the development of IFPRI's well-known global modeling tools on the climate–water–food nexus (see Chapter 4 for more about these models).

Microeconomic research on policies and incentives for improved sustainability

In terms of national policies and institutions to counteract water scarcity and pollution related to agrifood systems, research focused on: market instruments, such as the benefits of water markets (Rosegrant and Binswanger 1994); the role of governance, including water-user associations (Cernea and Meinzen-Dick 1994); the potential of farmer-managed irrigation systems (Kolavalli and Brewer 1999); multiple-use water systems (Meinzen-Dick and Bakker 1999); and paying farmers to use less water (Ringler 2007). Most of these research areas have since been incorporated into the mainstream of water policy and practice.

Another body of research focused on soil fertility and sustainable land management in degraded, drier, or less-favored environments (for example, Scherr and Hazell 1994). Research on sustainable land management and poverty across Africa, Asia, and Latin America advanced the concept of "development domains." These were defined as geographic areas with similar characteristics that determine the comparative advantage of different rural livelihood strategies. The concept of domains provided a useful framework to better target policy interventions based on a combination of biophysical and socioeconomic criteria (Chamberlin et al. 2006; Pender et al. 2006), and also laid the foundation for later analysis of the cost of land degradation and improvement. This analysis (Nkonya et al. 2016) presented novel methodological approaches to using publicly available data to assess the economic costs of land degradation, including costs related to loss of ecosystem services and associated impacts on human well-being. Results suggest that the studied investments in land restoration have an average return-on-investment ratio of 5:1.

Research on property rights and natural resource institutions

Research by IFPRI and partner organizations also reflected the growing recognition of the role of property rights, institutions, and good governance for ensuring sustainable use of water and other natural resources (Baland and Platteau 1996; Bruns and Meinzen-Dick 2000; Ostrom 1990; see also Chapter 6). A growing body of research evidence on the effectiveness of communities in managing resources, along with broad recognition of the failure of top-down solutions and blueprints, led to policies devolving management of forests, fisheries, rangelands, and irrigation systems from the state to user groups (Colfer and Bryon 2001; Meinzen-Dick et al. 2001; Vermillion 1997). However, rapid devolution did not always lead to sustainable or equitable management of these common pool resources, highlighting the need for effective governance institutions (Meinzen-Dick et al. 2002; Ostrom 2001) and participatory research that involves communities.

In response to growing demand from CGIAR Centers and other partners for research on the institutional foundations of sustainable management practices, IFPRI led the formation of CGIAR's systemwide program on Collective Action and Property Rights (CAPRi) in 1995. CAPRi brought attention to the important institutional foundations of many sustainable natural resource management practices, such as soil erosion control and community-led forest management, that have both large spatial scales and long time horizons. Specifically, the spatial scale requires coordination among communities and with government, while the timeframe highlights the importance of property rights in creating incentives and authority for investments and ongoing management. CAPRi's work also increased interest in the critical role of local communities in improving sustainability. Partnerships with nongovernmental organizations (NGOs) and other development and conservation actors helped identify ways to strengthen local institutions, such as in India (Box 5.1), and interest grew in community-based conservation of biodiversity and natural resources, including groundwater. While studying factors affecting local community action, this work also recognized the importance of government policies and coordination, especially at higher levels, and the need for adaptive collaborative management of resources (Colfer and Prabhu 2023).

BOX 5.1 **The Promise of Commons initiative in India: A success story**

Lessons from CAPRi engagements, including trainings for nongovernmental organizations (NGOs) and government actors, in India on the key role of institutions for collective action and property rights in advancing environmental sustainability resonated with the Foundation for Ecological Security (FES), a local NGO working on ecological restoration and improved livelihoods. This led to long-term collaboration between FES and CGIAR Centers in strengthening community-based institutions and the Promise of Commons initiative. This initiative supports communities in securing their rights to the commons, such as common grazing lands or forests, facilitates collective action through village institutions, and links these institutions to government programs providing additional resources to restore degraded lands. These approaches, informed by IFPRI and other CGIAR Centers, have now been applied in more than 48,000 communities across 14 states in India (FES 2023). A recent impact assessment of FES work in Rajasthan state found that it facilitated significant increases in tree cover as well as tree and shrub diversity and reduced forest encroachment, likely as a result of institutional strengthening (Hughes et al. 2024). This support for community-led management is particularly important given the large benefit streams from ecosystem services emanating from India's common lands, including both direct income-generating services as well as services supporting ecological resilience (Guo et al. 2024; Sandhu et al. 2023).

Behavioral and systemic approaches

Since 2000, there has also been an increasing focus on gendered behavioral systems—that is, the norms and rules governing how women and men behave in different societies and environments—which are explored in more depth in Chapters 6 and 14 of this book. There was particular interest in women's role in environmental stewardship, the sustainable use and management of natural resources, and technology adoption, on the one hand. On the other hand, some researchers explored how women are affected differently from men by environmental degradation, such as deforestation and water depletion, given their important roles in the collection of firewood and domestic water supply (for example, Agarwal 2013; Meinzen-Dick et al. 2014). Additional major conceptual advances were made through work on women's rights to land and other natural resources and on the linkage between soil health and gender (Doss and Meinzen-Dick 2020; Meinzen-Dick et al. 2019; Zhang et al. 2021).

In recent years, behavioral experiments—which use games to study how people behave in different situations—have examined the dynamics of management of common pool resources and environmental services (Cárdenas and Ostrom 2004). These experiments have contributed to a better understanding of the role of group characteristics (including gender composition), individual and group behaviors, and approaches to resolving social dilemmas around resource management and overcoming coordination and collective action problems in agri-environmental settings (Bell and Zhang 2016; Bell et al. 2016). Both experimental games and mixed-methods approaches can provide insights into how farmers and other users of natural resources respond to pro-environmental financial incentives and how communities select and implement rules to improve resource governance and encourage restoration. This same research also led to new insights, including that games originally designed to measure the propensity for communities to cooperate (Cárdenas and Ostrom 2004) can also be used as an intervention to strengthen collective action (Cárdenas and Carpenter 2005; Janssen 2023). Innovative adaptation of games, paired with debriefings of participants, has provided experiential learning about natural resource management and institutional capacity development and has catalyzed actions to enhance self-governance (ElDidi et al. 2024; Falk et al. 2023).

A systems approach has also been used to understand the relationship between landscape complexity and ecosystem services provision.[1] This work recognizes that biodiversity and ecosystem services underpin the stability and sustainability of agriculture and that both agriculture and many of these key ecological functions operate at the landscape scale. Policy research examined the potential of integrated landscape approaches for development and conservation (Estrada-Carmona et al. 2024; Waeber et al. 2023) and advanced the use of integrated land use and ecosystem service modeling to inform decision-making (Li et al. 2021). Affiliated systems research includes assessment of the climate change mitigation benefits of nature-based crop protection, the impacts of agricultural development pathways on biodiversity, and the economic valuation of land use and natural systems to inform policy and investment decisions.[2]

1 This work includes Chaplin-Kramer et al. (2019), Karp et al. (2018), Zhang, Kato, et al. (2018), and Zhang, Lu, et al. (2018).

2 On nature based crop protection, see Wyckhuys, Furlong, et al. (2022) and Wyckhuys, Zhang, et al. (2022); on biodiversity, see Flachsbarth et al. (2015); and on economic valuation, see Huang et al. (2018), Sandhu et al. (2023), and Hettiarachchi et al. (2023).

Research needs for a sustainable future

Poverty and food insecurity cannot be reduced sustainably without addressing the converging crises of climate change, biodiversity loss, and land degradation.[3] And while the need for action has been established, there is no consensus on where best to intervene, or how (Chappell and LaValle 2011; Phalan et al. 2011). Given this immense set of challenges, what direction should agrifood systems policy research take to best address environmental sustainability? Looking ahead, we see six main paths for future policy research and action.

Strengthen systems thinking in policy research within and across food and linked environmental systems

Environmental outcomes from agrifood system interventions are complex, uncertain, variable over time, and affected by multiple interlocking natural and human systems. Assessing such outcomes requires systems thinking and robust evaluation strategies that include transdisciplinary approaches. Assessment of multiple, heterogeneous effects and multi-objective impact measures, as well as models or research designs that adequately account for behavior change at various scales, will be essential. The Economics of Ecosystems and Biodiversity for Agriculture and Food Evaluation Framework (TEEB 2018), to which IFPRI contributed, made the case for comprehensively measuring food system externalities, including positive and negative changes in ecosystem services and across all stages of the value chain. This work also provides the analytical framework for true cost accounting, the theme of two recent *State of Food and Agriculture* reports (FAO 2023, 2024).

Increasing the environmental sustainability of food systems, moreover, requires going beyond agricultural production systems. Water pollution, greenhouse gas emissions, and other forms of environmental degradation are also caused by food transportation, processing, and preparation (Ringler et al. 2018; Tassou et al. 2009).

Interest in addressing the role of dietary choices in environmental degradation has gained a lot of traction and is reflected in Sustainable Development Goal 12, which calls for sustainable consumption as well as production. The growing importance of environmental sustainability of diets is also reflected in the concept of "sustainable healthy diets" (FAO and WHO 2019), which requires balancing environmental and nutrition trade-offs and establishing

3 For discussion on this topic, see WFPF (2025), Berry et al. (2015), Lal (2009), Wheeler and von Braun (2013), and van der Sluijs and Vaage (2016).

coherent enabling and policy frameworks. This, in turn, requires stronger linkages between agrifood systems and health-policy actors for coordinated action in "win-win" areas, where improved nutrition and health interventions can also directly improve environmental outcomes (Clark et al. 2019). An example is the reduction of sugar consumption, which has both large health and large environmental benefits (Lee et al. 2020; Popkin and Ng 2021). Agrifood systems researchers should also work more closely with providers of alternative energy solutions to reduce the excessive reliance of "clean" energy on biofuel production. Biofuels are often derived from crops that require large amounts of land and water and chemical inputs, and as a result, their large-scale development has increased global food prices (Pimentel et al. 2009).

Double down on transdisciplinary research processes

Interdisciplinary research has identified policies, technologies, and institutions that can reduce the environmental footprint of agrifood systems. However, their implementation requires transdisciplinary approaches that actively engage farmer, pastoralist, fisher, and forest-dependent communities that are key stewards of our natural resource base (Enqvist et al. 2018), along with other key actors from government, civil society, and the private sector, to jointly identify and apply solutions. These transdisciplinary research approaches need to be applied to the holistic evaluation of agrifood systems' externalities, positive and negative, along with a comprehensive assessment of interventions across scales to identify and avoid any negative externalities or increased inequities.

The CGIAR 2022–2024 Research Portfolio created opportunities to deepen and enhance cross-Center collaborative research through the establishment of the Research Initiatives on Agroecological Transitions, Low-Emission Food Systems, Nature-Positive Solutions, and NEXUS Gains. Under these CGIAR Initiatives, transdisciplinary research in "living labs" and other collaborative and participatory action research processes combined biophysical and social science research to support actor groups in developing their own understanding and assessment of sustainability and crafting their own pathways toward sustainability. Living labs are place-based environments or spaces where innovation takes place in people's real-world settings with the goal of taking innovation out of formal, controlled "laboratory" environments. Principles of the Living Labs for People developed by CGIAR include co-production, gender equality and social inclusion, good governance, and institutional sustainability to advance existing and novel innovation processes (Habermann et al. 2023). In southeastern China, a living lab has emerged from various actor groups in Qingshan village aligning themselves with national policies on low-emission food systems transition and green growth. Low-carbon practices considered or adopted include composting, reducing emissions from waste burning, and producing rice more sustainably (Habermann et al. 2023). In Madhya Pradesh, India, visioning exercises in the agroecology living landscape (Bergamini et al. 2023) involving farmers, various government departments, the private sector, civil society, and researchers identified not only the technical innovations sought from agroecological innovations but also the relevant business models, policies, and behavior changes (Singh and Freed 2024). These approaches build on the tradition of participatory research on resource management with more systematic approaches to citizen science and involve a range of actors in identifying problems and solutions.

Strengthen political economy and policy process research

While sustainability-focused research has increasingly incorporated institutional and behavioral economics, limited implementation of tested interventions points to the need for a much stronger political economy focus and policy process research to address why policies are (or are not) adopted to drive improvement in environmental outcomes (see Chapter 15). This research should also improve the knowledge base on the enabling policy environment for "best-bet" environmental solutions as well as for removing hurdles to the adoption or diffusion of effective approaches. In particular, greater attention is needed to identify what will motivate different types of actors—from global and national political leaders to men and women in communities—to adopt policies and practices that account for long-term costs and benefits, including both those that are visible and externalities imposed on others.

Infuse an environmental justice lens in agrifood systems research

Environmental sustainability of agrifood systems cannot be achieved without environmental justice (see Chapter 4). This includes procedural and epistemic justice to ensure that those most disenfranchised by environmental degradation have a voice, that their knowledge systems are valued, and that they are involved in the development of solutions (Grafton et al. 2025). Work on women's empowerment (see Chapter 14), energy and water insecurity, and transdisciplinary research under the CGIAR Research Initiatives and new Science Programs and Accelerators provides a basis for strengthening attention to environmental justice.

Improve the incorporation of feedback loops in systems models

Most modeling systems, including those developed by CGIAR Centers, assess the impacts of climate change on food systems or the impacts of food systems on water depletion, without adequately incorporating feedback loops, such as the impacts of food systems on climate or the impact of long-term groundwater over-extraction on food security. Given the continued rapid degradation of environmental systems, more assessments of the direct impact of extreme water and land degradation on food security and livelihoods are needed, as well as assessments of how such increased degradation may constrain the options for jointly improving food security and biodiversity futures. Examples of areas needing more thorough assessment include tipping points of environmental change, such as peak glacier melt and peak groundwater depletion, which are expected to dramatically affect food production levels in South Asia, among other regions (Immerzeel et al. 2010), and ice mass losses that affect rice production in coastal lowland areas (Chen et al. 2012). Another example is the Atlantic Meridional Overturning Circulation collapse—potentially causing substantial cooling in the northern hemisphere paired with further warming and/or drying in parts of the southern hemisphere—which would make food production more challenging at a global level (Alcala 2021).

Accelerate game-changing innovations

The Green Revolution technologies were game-changing innovations with lasting food security benefits. Over the span of a few decades, tractors and combine harvesters replaced oxcarts, horse-drawn plows, and threshing boards, while high-yielding varieties and agrochemicals led to huge increases in primary productivity from the 1960s to 1980s. By drastically transforming established structures, these disruptive innovations created new markets, changed the very nature of agrifood production, and ultimately overtook well-established technologies.

In a similar way, emerging technologies such as modern forms of genome editing, alternative proteins, artificial intelligence, robotics, solar-powered irrigation and farming, and nature-based solutions such as agroecology can truly revolutionize the way in which food is grown and should be applied together (see Chapter 17) (Herrero et al. 2020). In particular, CRISPR/Cas9 is an advanced tool for gene editing that can dramatically improve crop yields, quality, and disease resistance (Aman Mohammadi et al. 2023). Artificial intelligence, similarly, is a breakthrough innovation that can benefit all components of food systems (Ben Ayed and Hanana 2021). Alternative proteins are another breakthrough that can dramatically reduce the environmental footprint of animal-source foods, but more research and policy engagement are required (Pingali et al. 2023). Moreover, new biodiversity-driven measures such as biological control, microbial soil inoculants, or science-based diversification tactics can be key enablers of a "greener revolution" (Snapp et al. 2010). The adoption of all of these game-changing innovations at scale can ensure food security for a swelling global population without disregarding human and planetary health. But just as with the Green Revolution, it is essential to examine emerging environmental and equity impacts of these technologies, rather than assuming that they provide technological panaceas.

Conclusions

The past 50 years have seen an expansion of research on sustainability in natural resource management within agriculture and in food systems more broadly, accompanied by advances in models, in metrics, and in understanding of the complexity and interconnectedness of these systems. Research has advanced from accepting environmental degradation as a byproduct to improving food security to identifying policies, institutions, and technologies that enhance food security without adversely affecting ecosystem health. Policy research has, furthermore, highlighted the need to involve resource users who are aware of the complexity of the socio-ecological conditions in development of policies and incentives for resource use.

Despite all of these advances, environmental crises of climate change, land degradation, and biodiversity loss are continuing to outpace our levels of action. To achieve food security now and in the future will require systems thinking that combines knowledge from multiple disciplines and resource users. It will also require careful assessment of political economy contexts and other factors that motivate actors at all levels from the local to the global to adopt technologies and practices that can sustain and enhance the resources that provide our food and livelihoods.

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