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EDITORIAL

Beyond the Green Revolution: A roadmap for sustainable food systems research and action

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1. Introduction

The Green Revolution produced remarkable achievements in increasing food supply while leading to a suite of compromises for economic, social, and environmental outcomes [1]—including ongoing needs for rural development [2], persistent widespread malnutrition [3] and the transgression of multiple planetary boundaries [4]. To sustainably meet the grand challenge of feeding a growing and more affluent population in the coming decades, there is wide recognition that food system transitions must build upon the benefits of past food system advances while overcoming their many shortcomings [5–7]—a problem further complicated by an increasingly interconnected food system [8–11] and its interactions with a changing climate [12–14]. Food system actors—including policy makers, corporations, farmers, and consumers—must meet this challenge while considering potentially conflicting priorities [15], such as environmental sustainability, economic viability, nutrition and human health, and resilience to climate change and other environmental and socio-political disruptions. Successfully navigating this deep and growing complexity to meet multiple goals simultaneously—while avoiding or minimizing tradeoffs (e.g. [16])—is the crux of achieving sustainable and resilient food systems. New thinking is needed to shed light on the solutions for food system sustainability and the pathways to its realization, including overcoming political economy constraints to effective policy change. Here we take the pulse of our emerging understanding of food system sustainability—drawing from new food systems work in this Focus Issue—and outline three key aims to guide future research and action.

2. Aim 1: Expanding the definition of 'sustainability'

The studies in this Focus Issue—and in the wider literature—demonstrate that there is no single way to define or measure sustainability in the context of food systems. Based on this diversity of studies, two main observations emerge: the bulk of research on food system sustainability has focused on environmental dimensions; and individual parts of the food supply chain (as opposed to the broader food system) are often the focus. There is a dominance of climate change impact or exposure studies [5, 12–14, 17–21]. For instance, Tubiello *et al* [5] investigated the impacts of the food system on climate change, estimating that one-third of human-made GHG emissions are from food systems. In the other direction (i.e. climate impacts on food systems), Niles *et al* [13] found significant associations of temperature and precipitation variability with changes in diet diversity. A host of studies also explore other environmental pressures from food systems (mostly at the food production stage). Water-focused analyses demonstrated that a large portion of global food supply relies on unsustainable irrigation withdrawals [22], in particular from groundwater (e.g. in India [7]), that trade links places of consumption with distal locations of water scarcity [8, 11] and that the sustainable expansion of irrigation may be insufficient to meet future food demand [23]. Nutrient-focused studies by Kim *et al* [6] and Roy *et al* [24] identified solutions to address the challenge of reducing nitrogen pollution from croplands. All of this work provides a strong basis for future research that also considers a suite of social and economic dimensions of food system sustainability [25]—including challenges related to equity, access (e.g. [26]), farmer livelihoods (e.g. [27, 28]), affordability (e.g. [16]), and consumer health and well-being—and that takes a broader view of the entire food system (e.g. food environments, individual factors, and behavior) beyond just food supply chains [29]. An important research challenge when aiming for this will be to develop tools and metrics that are responsive to the information needs of stakeholders, that align actions from local to global scales, and that account for unavoidable inter-regional dependencies (e.g. via trade [9, 10, 30]) which can complicate solution design and implementation.

3. Aim 2: Identifying and quantifying synergies and tradeoffs

Quantifying multiple dimensions of food system sustainability can enable the development of conventional and novel solutions that amplify co-benefits and minimize trade-offs, as demonstrated by several studies in this Focus Issue. For instance, Smith *et al* [31] explore the potential of increased insect consumption to increase nutrition security in Africa and Asia, concluding that even a marginal addition of insects to people's diet would bring large nutritional benefits relatively sustainably. Koehn *et al* [32] quantify the GHG benefits of encouraging greater seafood consumption to move towards more sustainable diets, while Wei and Davis [33] show the environmental, nutritional, and climate resilience benefits of culturally appropriate dietary shifts. MacDougall *et al* [19] also show that the potential of microbial biomass cultivation technology to reduce the land and water footprints of traditional agriculture is feasible from a climate change mitigation perspective only after a low-carbon energy transition. While measuring multiple dimensions of sustainability can allow for the development of technical solutions for food supply chains, other studies in this Focus Issue make the important point that these food supply chains operate within a broader set of political, economic, legal, and social contexts which are essential to take into account. For instance, Mondal *et al* [34] show that agricultural interventions alone are insufficient to achieve year-round food security in rural India. Witt *et al* [35] demonstrate that the influence of environmental values can dictate public trust in food system actors. Through their examination of household food sharing in Zambia, von Gnechten *et al* [36] also show the role that informal networks can play in making food systems more sustainable and resilient.

Thus, even with improved quantification of multiple food system dimensions, this complexity of the food system presents substantial challenges for the identification of solutions. Attempts to direct the food system to a given goal can shift the state of other interconnected systems, creating unintended outcomes and circular feedback loops that may support or act against the intended goal of a policy, investment, or action. As such, knowledge co-development with stakeholders can help uncover novel solutions and synergies and minimize risks of undesirable outcomes or trade-offs [37]. Further, evaluating food systems within a 'systems-of-systems' framework can help elucidate and manage tradeoffs and leverage synergies [38]. Such an approach is limited in practice, however, because we still lack requisite data and understanding of system processes and interlinkages. For instance, policies aiming to reduce greenhouse gas emissions from the food sector require better quantification of emissions from different components of the food system, ranging from fertilizer production to land use change or transportation [37]. However, changes to reduce emissions from one system element may shift human behavior or natural processes, ultimately leading to greater emissions than before [37]. Moreover, actions to transition the food system to a more sustainable state may lead to unintended consequences and even unpredictable tipping points within ecosystems, socioeconomic systems, or political systems. The research community needs to map out these interlinking systems, identify areas where knowledge gaps persist, and establish a research agenda that systematically addresses remaining knowledge and data gaps.

4. Aim 3: Linking solutions with action

Addressing global food system challenges requires both solutions that account for synergies and trade-offs as well as action at multiple levels of governance that takes a holistic perspective of the problem. Because food systems encompass the entire value chain from production to consumption and nutrition, a convergence of agricultural, health, nutritional, economic, and environmental goals is critical. The studies in this Focus Issue make important advances in this regard and point to an immediate need to interactively link multidimensional solutions with policy and decision making (e.g. [37]). Traditionally, agriculture, environment, health, trade, economic development, and many other sustainability challenges relevant to food systems have been looked at through mandates of individual ministries. Bringing alignment between various departmental silos to meet food security, health and nutrition, and environmental goals will be critical for a food system that works for all people and the planet. While technologies and management practices for more efficient and sustainable production systems are available and can be very effective, distorted policy incentives, such as producer subsidies, have limited their adoption and use [39]. Policy reform has often been inhibited by political economy constraints at both the producer and the consumer end. Quantifying the environmental and health externalities of current food systems can contribute to assessing trade-offs and evidence-based advocacy for better policies (e.g. [40, 41]). Investments in data systems, at all scales, that provide accurate and timely information on the state of food systems are crucial (e.g. [15]). Modern information/communication technologies could help leapfrog capacity and infrastructural constraints facing statistical systems in developing countries [42]. Finally, behavior change among all actors across the food value chain is required to encourage sustainable intensification and to enhance the supply of safe and healthy foods. Such positive changes in consumer behavior and attitudes can reinforce the demand for better quality food that is produced sustainably [43]. To this end, the current global focus on food systems as the cause of environmental and health concerns—and transformed food systems as a potential solution to these problems—may provide an opportunity for a renewed push for policy change for better production practices and consumption behaviors.

5. A vision for achieving sustainable food systems

Food system sustainability presents a complex and multidimensional challenge (e.g. [44]). By seeking to achieve the three Aims detailed here and explored throughout this Focus Issue, the research community can play an invaluable role in providing the scientific evidence needed to ground decision-making and to ensure equitable benefits to food system stakeholders across spatial and temporal scales. Definitions of sustainability must be measurable—to be able to assess progress towards targets—and developed in close collaboration with stakeholders to quantify the outcomes that they hold in priority. These measurements of food system sustainability must span multiple economic, social, and environmental dimensions to provide a holistic picture of the current state of the system and to objectively assess the emergence of co-benefits or tradeoffs under system changes and interventions. Combining a detailed understanding of stakeholder needs with knowledge of the linkages, interactions, and feedbacks occurring within a food system can ultimately permit the development of solutions that are politically and socially feasible and produce benefits across a suite of outcomes. In this way, humanity can continue to realize the benefits of the Green Revolution while moving beyond its shortcomings.

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