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Research needs for a food system transition

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Abstract
The global food system, and animal agriculture in particular, is a major and growing contributor to climate change, land system change, biodiversity loss, water consumption and contamination, and environmental pollution. The copious production and consumption of animal products are also contributing to increasingly negative public health outcomes, particularly in wealthy and rapidly industrializing countries, and result in the slaughter of trillions of animals each year. These impacts are motivating calls for reduced reliance on animal-based products and increased use of replacement plant-based products. However, our understanding of how the production and consumption of animal products, as well as plant-based alternatives, interact with important dimensions of human and environment systems is incomplete across space and time. This inhibits comprehensively envisioning global and regional food system transitions and planning to manage the costs and synergies thereof. We therefore propose a cross-disciplinary research agenda on future target-based scenarios for food system transformation that has at its core three main activities: (1) data collection and analysis at the intersection of animal agriculture, the environment, and societal well-being, (2) the construction of target-based scenarios for animal products informed by these new data and empirical understandings, and (3) the evaluation of impacts, unintended consequences, co-benefits, and trade-offs of these target-based scenarios to help inform decision-making.

Keywords Animal agriculture · Plant based · Scenarios

1 Introduction

Humans now industrially manage, slaughter, and consume billions of terrestrial (Schlottmann and Sebo 2018) and trillions of aquatic animals each year to fulfill growing animal product demands. As a result, global animal agriculture is now among the largest drivers of global environmental change, contributing to at least 14.5% of greenhouse gas emissions;

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disruption of biogeochemical flows; biodiversity and wild animal losses; copious land, energy, and water consumption (Richter et al. 2020); air and water pollution (Poore and Nemecek 2018; Domingo et al. 2021); and ecosystem destabilization (Campbell et al. 2017; Springmann et al. 2018).

Despite the enormity of animal agriculture, global food and nutrition insecurity is still both pervasive and persistent. This sector is currently largely structured to serve the industrialized world and wealthier population segments (Schiller et al. 2018; Willett et al. 2019a; The Economist Intelligence Unit 2021). Given the disproportionate natural resources used for animal products relative to plant products, dietary changes are necessary to achieve net-zero emissions (and mitigate other environmental consequences) while also addressing food security concerns globally.

Furthermore, a food production system that is compatible with limiting global warming to 1.5 or 2 °C entails major dietary changes (Shukla et al. 2019), including in the consumption of animal products with high environmental impact (Clark et al. 2020b). Lastly, as research and evidence on animal welfare, suffering, and sentience increases, so too should our practice of viewing animals as industrialized food resources (Commission 2009; Schlottmann and Sebo 2018). There is thus a need to reconsider our approach to global agriculture, and reducing reliance on animal agriculture is one of the most important ways we can reduce both our environmental impacts and impacts on individual animals while also providing nutritious food for all (Springmann et al. 2016a; Scherer et al. 2019).

However, global and regional food policies and economics are currently oriented towards increasing animal agriculture, and it is not well understood exactly how trends and transitions in production and consumption of these myriad animal products, nor the plant-based products that could replace them, may interact and impact key aspects of social and environmental systems and at finer regional and local scales. Therefore, achieving the goal of reduced reliance on animal agriculture requires a new, cross-disciplinary research agenda focused on (1) data collection and analysis at the intersection of animal agriculture, the environment, and societal well-being (inclusive of socio-economic development and public health); (2) the construction of target-based scenarios for animal products informed by these new data and empirical understandings; and (3) the evaluation of impacts, unintended consequences, co-benefits, and trade-offs (e.g., across the Sustainable Development Goals, biodiversity, human nutrition, jobs) of these target-based scenarios, which can help inform possible policy options and decision-making.

2 Regional and sectoral research gaps in assessing impacts of dietary change

Some recent work has framed the agricultural solution space to global environmental change as a pursuit of "planetary health," inclusive of both food and nutrition security and ecological and climate sustainability (Willett et al. 2019a, b). Key to the planetary health framing is the idea that human health is underpinned by the health of our environment and climate, and that disruptions in the latter are inextricably linked to deterioration in the former. The fact that this frame was advanced largely by the public health community is an important indicator of the convergent, transdisciplinary nature of this overall work.

In this framework, the global-scale planetary boundaries (Steffen et al. 2015) are used to assess the current environmental footprint of agriculture as related to production, consumption, and waste across the supply chain (Campbell et al. 2017; Springmann et al. 2018).

Large-scale modifications are required on each of these dimensions in order to return to an ecological and climate "safe operating space." Improved production and reduced waste alone are not found sufficient—a change in dietary patterns was also found to be of urgent need (Willett et al. 2019b). While there are critiques and limitations of the planetary boundaries framework (Biermann and Kim 2020), our intent here is primarily to document previous work looking at the intersection of agriculture, environment, public health, and socio-economics. Beyond this framework, there is furthermore increasingly broad acceptance that dietary changes will be necessary to achieve climate mitigation and deep decarbonization (Nabuurs et al. (2022); Shukla et al. 2019).

Augmenting this work, the EAT-Lancet commission advanced a recommended "diet for planetary health" that called for greater than 50% reductions of red meat consumption, across wealthy and industrializing economies (Willett et al. 2019) and a movement towards more plant-based diets globally. This recommended diet constitutes one potential alternative food system scenario at the global scale. However, regionally or country-specific targets (or context-specific interpretations of this target) were not specified, nor were other possible scenarios explored in this report.

Nevertheless, beyond the initial EAT-Lancet reports, there is an emerging body of independent work quantifying the global ecological, environmental, and climate impacts of dietary shifts. For example, idealized scenario-based modeling approaches of dietary change show that the largest global climate change mitigation potentials occur with a population-wide shift to vegan diets, although significant gains may also be had with more incremental plant-based consumption (Springmann et al. 2016a; Kim et al. 2020). These idealized dietary scenarios may also produce positive human health impacts (Springmann et al. 2016b; Reinhardt et al. 2020). Other approaches have compared the environmental and climate outcomes of specific (i.e., World Health Organization) dietary guidelines, finding significant variation in both the outcomes and the prescribed composition of different diets (Tom et al. 2016; Shepon et al. 2016; Ritchie et al. 2018). More recent work is exploring how dietary shifts may impact and intersect with global biodiversity goals vis a vis land use and land cover changes (Kok et al. 2018; Henry et al. 2019; Leclere et al. 2020).

Much of this work is conducted at the global scale or for large regional aggregations, and/or is focused on assessing potentials for dietary shifts to advance environmental and public health goals. Such work is important to exploring the range of target-based food system scenarios that should be studied more systematically, akin to scenarios developed for climate change research (discussed below). However, there is still limited understanding of the inter-sectoral impacts and influences of dietary shifts, including possible co-benefits and trade-offs (including socio-economic) that must be considered across a range of spatial scales (e.g., rural-to-urban) and temporal trajectories (e.g., now to end-of-century) in order to better explore the ramifications of meeting target scenarios and eventually developing the range of pathways to achieve them. These critical research gaps on how to achieve these goals remain unresolved across both spatial and temporal dimensions.

Additional work is needed to improve our understanding of dietary interactions in human and natural systems, across sectors, and at multiple spatial and temporal scales, particularly in relation to animal agriculture products given their outsized environmental and climate impacts. This is important because decision-makers operating on national or even sub-national levels require trade-off and co-benefit assessments of how altering a range of food system processes (e.g., production, supply chain management, consumption trends) to meet various large-scale goals impacts key social, economic, and environmental metrics in their jurisdictions. Negative trade-offs across these metrics at national or sub-national levels can pose serious barriers to achieving these large-scale dietary goals, while net co-benefits could help to advance such policies (Wellesley et al. 2015).

3 Data limitations on understanding the role of animal products in human and natural systems

While critical to decision-making on future food production and consumption, our understanding of how animal agriculture products, and the plant-based products intended to substitute for them, interact with both human and environmental systems is still highly incomplete. A foundational task for a transformative food system research agenda therefore includes improved data collection, and just as important, the vetting and creation of appropriate measures at the intersection of environment, socio-economics, and human and non-human animal health concerns. Despite recent efforts to characterize the sustainability of agriculture at the country level using both biophysical and socio-economic indicators (Zhang et al. 2021), many countries lack or are not reporting the needed data. This complicates both assessing their agricultural sustainability and comparing across countries and dimensions.

Gaps in our understanding of how the production and consumption of animal products interact with dimensions of human and natural systems result from a sheer lack of data, e.g., for particular sectors/dimensions and/or at finer spatial scales; sparse and/or discontinuous time series (temporal and spatial) data that inhibit longer-term trend analyses; and uncertainties about the data themselves, their appropriateness, and what exact processes or phenomena they capture. The latter is particularly problematic for aggregate metrics and normalized indicators commonly used to monitor human socio-economic development and well-being, as well as environmental and climate impacts.

More progress on data collection and analysis has been made on some key dimensions than on others. For example, recent work has endeavored to quantify the climate and environmental impacts of various meat and dairy products (Poore and Nemecek 2018; Hayek and Garrett 2018; Pieper et al. 2020), diets on a regional and country basis (Heller et al. 2020; Kim et al. 2020), and even with respect to specific firms (GRAIN and IATP 2018; Lazarus et al. 2021). Nevertheless, uncertainties and limitations persist primarily stemming from reconciling different life-cycle assessment methodologies that quantify foodstuffs environmental impacts (Poore and Nemecek 2018; Clark et al. 2020a); adequately measuring GHG fluxes and carbon sequestration in global agricultural lands (Smith et al. 2020b, a); and quantifying and reporting actual agricultural water and nutrient use (Lu and Tian 2017). Furthermore, while many snapshots or time slices (e.g., circa 2000) of global agricultural environmental impacts exist, major data limitations are inherent in capturing the heterogeneity of these environmental impacts across space and time. One example is that of soil health and fertility—a major focus of recent food security and climate change mitigation goals (Bossio et al. 2020). However, measuring (and even defining) soil health and fertility is a complex task (Smith et al. 2020c), owing to both geospatial variation and numerous simultaneous biogeochemical and physical processes. As such, more reductive metrics, such as soil erosion, are often used as a proxy (Zhang et al. 2021).

The social dimensions of food systems as they relate to human diets are less resolved and more data-limited across space and time than the environmental dimensions. Key to understanding human food and nutrition security is not just what people eat (about which there is comparatively more data) but also when and how food is consumed, for which data is less available particularly in developing countries and regions (Fanzo et al. 2020). Major food security indicators (e.g., the prevalence of undernourishment (FAO et al. 2018)) are available for the majority of countries only for the recent past (and some not at all), and so resolving and understanding time-varying and/or sub-national trends are challenging.

Beyond food security, food preferences (and their dynamic nature), particularly in emerging economies with the most pronounced animal product consumption trends, must be better elucidated.

There is also a need to better understand the state and dynamics of human labor in the animal agriculture supply chain, from farming and on-farm labor to meatpacking, particularly outside industrialized nations. In this regard, not only the number of jobs, but the quality, safety, and security of jobs must be considered. For example, very recent work has shown that animal meat processing jobs are associated with high risks of injury and illness across multiple (industrialized) countries and contexts, particularly during the ongoing COVID-19 crisis (Middleton et al. 2020). Similarly, large uncertainties also lie in assessing the hazards of jobs in production and processing of plant-based alternatives to animal products (Harmse et al. 2016; Leibler et al. 2017).

Even considering food production alone, participation and labor are driven by myriad forces, including market prices for producers who have access to capital for resource-intensive commodity production and sheer necessity for smallholders who have inherited small parcels of land or convert nearby habitat for subsistence production. As such, land use and management decisions display large variability across space and time (Malek and Verburg 2020). Understanding this and quantifying key aspects of the animal product workforce are important because shifting diets may incur major changes to cropping patterns and management practices that alter job availabilities and required skillsets. Improved baseline data on the current workforce producing animal products is required to better understand the impact on food producers and to inform policies that enable effective transitions.

In addition, while aggregate (i.e., national) data on farming systems and activities are reported annually to publicly available platforms like the United Nations Food and Agriculture Organization, data at sub-national scales are not readily available and/or accessible across all countries. Particularly across developing states and areas, many of which are highly agriculturally dependent, detailed data on sub-national agricultural systems including both animal- and plant-based product are more challenging to obtain. This can limit identifying the extent to which regional producers (and consumers) rely on different domestically grown animal- or plant-based food sources, and related agricultural activities, and how trends in the production of these foods impact regional consumption and vice versa.

Similarly, dedicated data collection is also required to ascertain sub-national consumption trends, in both animal- and plant-based foods, particularly along rural–urban gradients. National nutrition and food security surveys, where available, are important sources of information in this regard, but not all countries conduct such surveys (or conduct them regularly) and they may not capture important temporal dimensions related to the consumption of different protein sources. Moreover, while data on international trade in major agricultural commodities is readily available, it is harder to assess the amount of agricultural products embedded in international trade in processed food items.

Beyond simply collecting the above-described data, there is a need for such data to be organized in such a way that they can be analyzed together meaningfully. Ideally, the variables and indicators would, for example, support comparable temporal resolutions and represent key modes of variation for national and sub-national contexts both spatially and temporally. This may include, for example, regional (e.g., urban vs rural) variation in the production and consumption of animal- and plant-based products as well as time-varying trends owing to socio-economic development and food system dynamics and shocks.

Some relevant indicators (such as the socio-economic indicators listed by Zhang et al.) are aggregate composites of, or derived from, other indicators (Maxwell et al. 2013; The

Economist Intelligence Unit 2021). This may obscure embedded uncertainties and limitations which should be elucidated and understood. How different indicators and variables are calculated and normalized should also be scrutinized.

An example of indicators as aggregate composites of other indicators is found in the attempts to quantify the overall climate change contribution of the agricultural sector. Indicators such as Global Warming Potential* (GWP*) among others (Allen et al. 2016; Cain et al. 2019) are meant to provide the basis for an aggregate measure of warming resulting from different species of GHGs (e.g., carbon dioxide and methane) which have dramatically different properties. However, the choice of an emissions-related warming metric, and the scale of its application (global vs national or sectoral), can lead to differing conclusions and potentially different outcomes for mitigation, particularly in the animal agriculture sector. GWP*, for instance, takes as reference the current emissions of different GHG species against which to assess future change in emissions and warming. While GWP* may better represent the more immediate influence of methane on future warming trends at the global scale, it risks heavily discounting methane from industrialized nations like the USA (Rogelj and Schleussner 2019), where the ruminant agriculture sectoral growth may be plateauing (but is still largely increased from pre-industrial levels). Such indicators may minimize the role of industrial animal agriculture and thus the need for climate mitigation in wealthy countries (Ridoutt 2021; Liu et al. 2021), thus potentially distorting judgments of equity and responsibility between developing and industrialized nations (Rogelj and Schleussner 2019).

4 Towards transformative food system scenarios

Comprehensive data collection at the intersection of social, economic, and environmental dimensions, alongside the integration of more disciplines ranging from human development to animal well-being (Sebo 2022; Drewnowski and Poulain 2018), will enable more complete analyses of how animal production and consumption influence and interact with human and natural systems. Such analyses are, in turn, integral to developing global and regional scenarios for reducing reliance on animal agriculture and enabling the production and consumption of more plant alternatives. For example, understanding how current socio-economic development or agricultural policies across different regions and contexts influence the production and consumption of animal products (and vice versa) can help establish “baseline” or “business as usual” reference points against which to measure change. Beyond baseline scenarios, several comparison scenarios can be developed that represent varying degrees of ambition in food system transitions and capture the full uncertainty space (e.g., range of decision-making) across dietary changes, making clear both the positive and negative impacts that transformative food system change can have on meeting sustainable development goals (Wellesley et al. 2015; Drewnowski and Poulain 2018).

Likewise, scenarios for animal product—and alternatives—production and consumption have many ramifications for the trajectories of socio-economic development (particularly rural and agricultural development) and for global environmental and climate change (Springmann et al. 2016a, b, 2020). Therefore, scenarios of food system change should maintain consistency with other widely used narratives of future change, specifically the Shared-Socioeconomic Pathways (SSPs) (Riahi et al. 2017; Rogelj et al. 2018; O’Neill et al. 2020) used in the assessment reports of the Intergovernmental Panel on Climate Change (IPCC) and include land use and land cover change alongside trajectories of various climate forcings, and the Representative Agricultural Pathways (RAPs) (Antle et al. 2014; Valdivia et al. 2015) that more explicitly capture uncertainties and possibilities of regional- and country-level agricultural development (both briefly described below). Furthermore, the methodologies behind the design and architecture of these existing and widely used SSPs and RAPs serve as highly useful starting points to develop transformative food system scenarios.

There is much precedent for the development of “representative pathways” of future global change, particularly among the IPCC’s five SSPs (Riahi et al. 2017)—narrative scenarios that detail five global “futures” for socio-economic development with cross-sectoral ramifications. SSP1, for example, provides a sustainable development scenario where the “world shifts gradually, but pervasively, towards more inclusive development that respects perceived environmental boundaries.”

The SSP framework invokes a “pathways” terminology, which may be difficult to disentangle from “scenarios.” However, following Aguiar et al. (2020), we distinguish between “scenarios” and “pathways” in the following way. We take the term “pathways” to represent a set of decision-making trajectories that result in a particular target-based scenario. Our specific interest, however, is to develop a research agenda that can help inform and set target-based scenarios for food system transformation. Resolving pathways of change would require moving beyond the research agenda described here to also include insights on food system power structures and politics that also greatly shape how decisions are made beyond data and targets alone (e.g., Clapp 2022).

These scenarios are characterized by trends across key sectors consistent with their respective narratives. These SSP-RCP have been applied to a range of sectoral impacts assessment (number of applications in blue and green colors in Fig. 1), including agriculture, water, public health, biodiversity, and resources use and availability.

These SSP-RCP combinations also incorporate corresponding land use pathways differentiated by level of regulation, agricultural productivity, dietary preferences, trade patterns, globalization, and climate mitigation approaches (Popp et al. 2017). We note that these SSPs do include assumptions regarding dietary change, broadly reductions or increases in consumption of animal-sourced foods that correspond to the land use pathways of various SSP-RCP combinations. However, these scenarios do not consider in detail how combined shifts in both the production and consumption of specific animal products, alongside potential avenues for specific plant-based substitutions, can meet both climate (environmental) and human development goals on different temporal and spatial scales.

This research gap may be partly addressed by leveraging methods and protocols developed under the auspices of the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Rosenzweig et al. 2013). For example, AgMIP has advanced recommendations of how agricultural system representations in Integrated Assessment Models, used to design and test the SSPs, can be improved to go beyond land use land cover change and better resolve key biophysical agricultural drivers (e.g., GHG and input use), responses (e.g., crop yields), and feedbacks to climate change and global economic trends. Incorporating these recommendations would also enable better identification of “unintended consequences” for agriculture and by extension food security that result from socio-economic trends (Ruane et al. 2017).

In addition, AgMIP has established protocols for constructing regional and global Representative Agricultural Pathways. RAPs are narratives of regional and global agricultural development constructed to be consistent with the global-level SSPs while also incorporating more detail on regional- and country-specific crop and agricultural system change parameters (e.g., yield improvement, input availability, and agricultural system design)

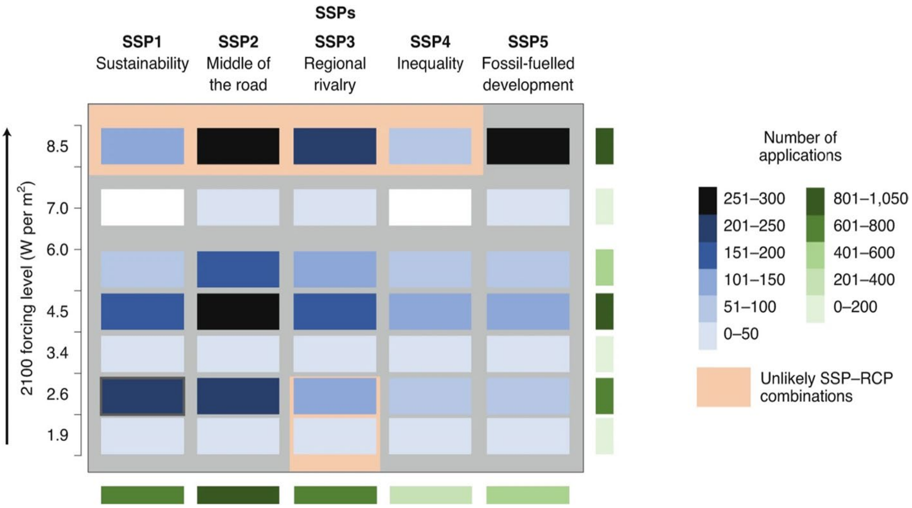

Fig. 1 Reprinted from O'Neill et al. (2020). Radiative forcing scenarios (per the Representative Concentration Pathways of GHG emissions) are shown on the *y*-axis. Each column represents a different SSP—scenarios of socio-economic development, inclusive of energy and land use pathways among other sectors, from sustainability to fossil-fueled development and several intermediate/alternative trajectories. Pink shading indicates unlikely combinations, while the blue or green colors indicate the number of sectoral impact applications (i.e., studies/analyses out of 1370 reviewed by O'Neill et al. (2020)), e.g., agriculture, water, public health, biodiversity, and resources use and availability, that have used a particular SSP-RCP combination or overall SSP, respectively. White indicates that these scenarios have not been used in any known studies/applications

that were not fully resolved as part of the SSP development process. RAPs can thus better resolve, from a socio-economic perspective, how the larger-scale SSP-RCPs may affect regional agriculture, inclusive of changes in preferred or dominant crop varieties, farming systems, national-level agricultural policy, and its subsequent impacts on management (e.g., labor, seed, fertilizer, water resources) (Valdivia et al. 2015). Developing these RAPs can be useful to both research and applied/stakeholder communities across many sectors in several different ways. First, target-based scenario analyses and comparisons can help bracket the uncertainty embedded in global policy and decision-making, as well as provide a multi-parameter framework to assess model (e.g., climate or sectoral) response sensitivity. We note that in order to evaluate more ambitious and transformative food system scenarios, i.e., a movement towards largely plant-based global food production and consumption, the assumptions and specifications in models used to analyze change and impacts must be made more flexible, as current model structures can unintentionally limit the scope of potential change (Ruane et al. 2017; Weyant 2017). Second, they quantify for stakeholders an envelope of potential changes and responses to shifting policies and/or decisions. Third, taking the SSP-RCP combinations as an example, they enable "integrated analyses" of future climate impacts, vulnerabilities, adaptation, and mitigation.

An idealized set of possible scenarios are shown for cattle meat production in Fig. 2. To bracket uncertainty, transformative food system scenarios should range from high-ambition reductions in animal products, alongside major upscaling of plants and plant-based alternatives, to scenarios that extrapolate current demand trends, similar to the SSPs. The improved data and analyses obtained from filling the research gaps that we have identified

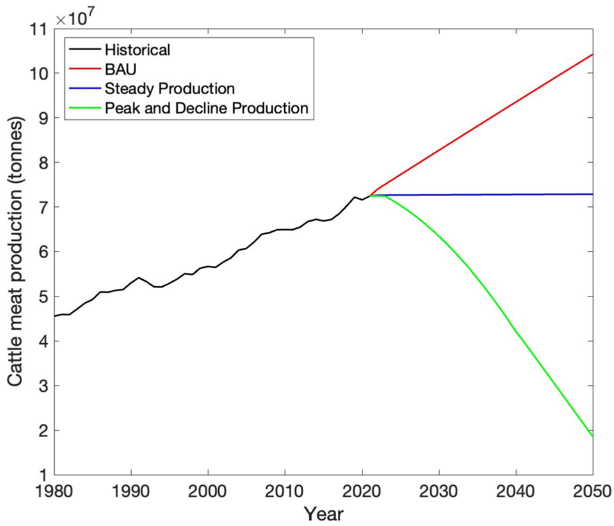

Fig. 2 Illustrative depiction of idealized food system scenarios with respect to global cattle meat production, as an example. Corresponding scenarios would exist for other animal products' production (and consumption), as well as plant-based alternative products. "Historical" shows actual cattle meat production (from 1980) based on world aggregated UN FAO statistics. The black dashed lines represent a possible period of transition for implementation and scaling of production of alternatives, and colors represent possible future pathways of production, ranging from "Business as Usual" (BAU, red) to peak and declining production (green)

will help researchers quantify uncertainties and identify key cross-sectoral impacts, synergies, and trade-offs that may ultimately lead to the development of a set of trajectories or pathways to achieve food system targets or scenarios at varying degrees of ambition.

Along these lines, it is important to note that animal agriculture is not homogenous and relies on a diversity of animals (e.g., cattle, poultry, pigs, aquaculture) and production systems (e.g., concentrated industrial, rangelands/pastoral, integrated animal-cropping systems), with high regional variation owing to social, cultural, political, and economic conditions. Moreover, within and across animal products, there is variation in environmental impacts, efficiencies, regional production systems, and social and cultural preferences.

Evaluating dietary change scenarios that capture this heterogeneity in animal products and systems would help identify to what extent production-side improvements to existing animal systems could meet combined climate/environment and socio-economic goals. This includes, for example, scenarios that shift red meat consumption in the western industrialized context towards poultry (and the potential externalities this shift may incur), while increasing the production and consumption of various species in developing contexts (Willett et al. 2019b).

However, animal products generally have more significant environmental impacts (e.g., on greenhouse gas emissions) than even the most intensive plant products (Poore and Nemecek 2018), and thus, a first-order evaluation of scenarios globally shifting current diets from all animal sources to plant sources provides useful information. There are also debates on animal-to-animal substitutions in food system transformations, and the distributed consequences of these for the environment, people, and animal welfare (Chan et al. 2022).

5 Key questions to explore transformative food system scenarios and their role in decision-making

Evaluating and quantifying the impacts of different food system scenarios, and developing an envelope of decision-making trajectories to do so, are foundational to designing appropriate and responsive policy interventions needed to facilitate sustainable food systems development. More specifically, transformative scenarios allow us to ask and make progress in answering the following kinds of questions: How do the environmental and nutritional impacts associated with an intensive global shift towards plant products compare with those of an increasing animal product demand scenario? What are the associated trade-offs between rural livelihoods and rural–urban economic inequities? What are the impacts on food security and nutritional outcomes in vulnerable areas? What are short- vs. long-term implications of different scenarios on environmental, social, and economic outcomes?

Recent work has called attention to the kinds of questions that the development of transformative food system scenarios may well help answer. One example is the impact of food system transitions (from animal to plant based) on agricultural labor and supply chain jobs (e.g., processing and meat packing). It is estimated that the animal agriculture sector employs ~ 1.3 billion people globally (Committee on Considerations for the Future of Animal Science Research 2015), and some countries' agricultural workforces are proportionally more dominated by animal production than others. These include high-income countries with a strong reliance on industrial animal agriculture, and also those countries/regions where pastoralism and diversified farming systems (including non-industrial animal rearing) are one of the few livelihood options (in the case of more arid environments) and/or are structured to reduce farming risks and provide social safety nets. It is also important to consider that, particularly in industrialized nations, existing rural–urban socio-economic inequities are further related to the differential consumption of animal-based products. It is important to understand and quantify how these inequities might be further complicated, exacerbated, or alleviated by plant-based transitions (Li and Jamieson 2022).

Understanding and quantifying such impacts are also important for understanding the potential for political support for such transitions. Recent simulations using cross-sectoral decarbonization scenarios focused on Latin America, which included plant-based food trajectories, demonstrate that such transitions could result in strong future job creation, exceeding that of more fossil fuel–driven development scenarios (Saget et al. 2020). While these results are instructive to regional decision-making, such trade-offs and/or co-benefit analyses could be even more useful if the tested scenarios of plant-based transitions were harmonized across different spatial scales (e.g., from global to sub-national as suggested for transformative food system scenarios), particularly given the globalized nature of animal production and consumption, and for different future time periods.

Impacts on human nutrition are another key dimension requiring evaluation using transformative food system scenarios. The recent EAT-Lancet report highlighted important regional disparities in the consumption of animal- and plant-based foods (i.e., fruits and vegetables), which tend to track wealth and industrialization. Populations that are highly vulnerable to climate change and other public health hazards, poverty, and malnutrition, particularly in childhood, likely also experience a large deficit in regular consumption of key macro- and micronutrients, including protein. For these populations, increases in animal agriculture may prove beneficial to public health (Willett et al. 2019a). Other, wealthier populations consume excess animal products and protein specifically (Willett et al. 2019a, b). Complicating matters further are unresolved questions about optimal protein consumption. It will be important to understand how various food system scenarios impact these geospatial availability and consumption discrepancies in animal and plant products at national and sub-national scales (e.g., rural–urban gradients) in order to develop governance options that help to minimize trade-offs and maximize co-benefits. In addition, while much of the current discussion on reducing animal agriculture focuses on industrialized economies (which dominate animal consumption), the scaling up of plant-based options to serve nutrition needs of emerging economies will become increasingly relevant due, e.g., in urban China where animal product consumption is rapidly increasing. Even in food insecure and vulnerable populations, an enhanced focus on nutrition security rather than just food security alone underscores the need to develop sustainable, accessible food options.

Scenarios of food system transformation, the resulting quantification of impacts, tradeoffs, and co-benefits, as well as the identification of key sources of uncertainty including those that may result from the production of new knowledge (Jamieson 1996), can provide important information for stakeholders and those charged with creating laws, policies, and guidelines regarding agriculture, climate/environment, public health, and animal welfare. Transformative food system scenarios may also help to ensure consistency in cross-sectoral decision-making and planning, for example, in National (climate) Adaptation Plans, Nationally Determined Contributions for greenhouse gas mitigation to the Paris Climate Agreement, and national nutrition guidelines and standards.

Nevertheless, while the research needs we identify are necessary to improve understanding of conventional and alternative food production, distribution, and consumption, this understanding alone is insufficient to spark global or even regional food system transitions. Understanding actual decision-making pathways to meet food system target scenarios is important as well, and these will in large part almost certainly depend on the status and influence of power structures embedded with the food system (Clapp 2018, 2021) that govern and constrain its political ecologies across space and time.

6 Conclusion

Scientific consensus is emerging that reduced reliance on global and regional animal agriculture; can help mitigate climate change and restore and conserve ecosystem services; and improve human health and animal welfare. Realizing these goals on a global scale requires a new research agenda to construct and comparatively analyze transformative food system scenarios at sub-regional scales. To this end, we suggest that key activities in such a research agenda include improved data collection and analysis at the intersection of animal product production/consumption and human and natural systems; the use of these data to inform development of current and future food system scenarios with varying degrees of ambition; and the use of these scenarios to evaluate trade-offs and co-benefits in support of decision-making pathways and policy creation. Critical to these research activities is the integration of many disciplines, spanning the natural and social sciences and humanities. Indeed, the sheer number of perspectives and disciplinary approaches required to envision a dietary transition towards plant-based food systems renders this pursuit among the most pressing societal grand challenges (Morris et al. 2021).

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M. H.: contributed to conceptualization of funded project and initial data analyses.

D. J.: contributed to conceptualization of funded project, manuscript, and manuscript writing.

G. H.: contributed to conceptualization of manuscript and manuscript writing.

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