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Article

Food and agriculture systems foresight study: Implications for gender, poverty, and nutrition

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Abstract

This review evaluates foresight studies to understand how the future agri-food system may impact gender, poverty, and nutrition (GPN). Foresight studies agree that it will be challenging to transform the agri-food system into one that is sustainable, healthy, and just, although the degree to which foresight studies consider GPN is uneven. Foresight work with a GPN focus tends to assume that global coordination of policies and regulations is both necessary and possible in order to achieve improved GPN outcomes. However, history has shown that efforts to coordinate globally are mixed. At the same time, innovation-led studies pay less attention to barriers to equitable adoption and nutritional outcomes. Yet, the history of development has demonstrated the difficulties of equitable implementation of and access to new technological innovations, particularly for women and marginalized populations. I argue that mainstreaming GPN into foresight research can inform both policy-led and innovation-led pathways that support an improved agri-food system. The use of multisectoral and multilevel tools and analyses can support future foresight research and policymaking to systematically identify the net influences on and trade-offs among GPN and other factors.

Keywords: Foresight, Food, Agriculture, Gender, Poverty, Nutrition

JEL codes: I3, J16, Q01, Q18, Q28, Q54

1 Introduction

Agricultural and food systems in the next 20–30 years will face substantial pressures. Numerous forces such as demographic waves, technological change, disease, climate change, and economic and political shifts will change what is grown by whom, how it reaches consumers, and what is consumed by whom. If current trends continue, malnutrition is expected to increase, poverty will likely worsen for some individuals, and some populations will face increased vulnerability (WEF 2017; FAO 2018a; Willett *et al.* 2019). At the same time, the agri-food system (AFS) can be harnessed to decrease poverty, improve nutrition, and improve gender equality, among other positive outcomes.

I aim to understand what foresight studies can tell us about the future relationships between the AFS and gender, poverty, and nutrition (GPN). Foresight is 'the act of thinking about the future to guide decisions today.' (Wiebe *et al.* 2018: 546). Three common foresight methods consider (1) anticipated trends and drivers impacting agricultural and food

systems, (2) variations in agricultural and food system scenarios, and (3) visions for future agricultural and food systems.

In this article, I highlight how and where GPN impacts might occur within the broader AFS. By evaluating foresight research in the broader context of the AFS, I aim to holistically understand the impact of a future technology, policy, or trend. With an eye toward the AFS, not only am I interested in whether the action will have its desired impact but also how such changes will influence or impact other outcomes, such as those related to GPN. A systems perspective can also support transparent conversations about trade-offs and synergies by bringing environmental and societal goals into conversation with food system actors and activities (Zurek *et al.* 2018; Ingram and Zurek 2019), can help practitioners, researchers, and policymakers avoid siloed thinking (WEF 2017; NAS 2019), and shows the influence of the AFS across several Sustainable Development Goals (SDGs) (Serraj *et al.* 2019).

This review finds that we know less about GPN-related impacts from foresight studies than we should. Not explicitly incorporating GPN outcomes into foresight work runs the risk of further entrenching inequalities and nutritional and gender disparities. Using a systems perspective, I also identify how GPN impacts may hinge on implicit assumptions made by foresight studies. For example, technology-focused studies that do not consider gendered barriers to technology adoption run the risk of promoting technologies that exacerbate gender inequality. I argue that there is a need for future foresight work to highlight interactions, trade-offs, and synergies across interventions and among outcomes. Doing so could support a deeper understanding of how GPN outcomes may be impacted. Without incorporating a broader food systems perspective that incorporates GPN, it remains challenging for decision-makers to weigh the relative merit of various foresight proposals and findings.

2 Approach and foresight methodologies

In this paper, I review documents identified by the CGIAR Independent Science for Development Council as relevant for their work to support One CGIAR efforts. I also include additional studies that focused on global or low-income-country food and agricultural foresight (e.g. FAO 2018a; Willett *et al.* 2019; Future Today Institute 2020) or had a strong poverty, gender, and/or nutrition lens as related to the future AFS (e.g. Quisumbing *et al.* 2019 on gender in Africa; Willett *et al.* 2019 on nutrition). See the bibliography for the full list of studies reviewed. Most reviewed foresight reports have a dominant theme, such as the future role of technology and science; the future role of markets (and governance); or the role of policy at subnational, national, and global levels.

I use an AFS lens to synthesize existing agriculture and food foresight studies. There are numerous definitions and examples of AFS (HLPE 2017; Zurek *et al.* 2018; FAO 2018a; Rosenzweig *et al.* 2020). I use a general definition of agricultural and food systems: integrated, multiscalar entities that include drivers, activities, actors, and outcomes (see Fig. 1). Drivers are macro-level factors that both directly and indirectly influence the food system and can include climate and climate variability, policy environments (including trade), and cultures and norms. Research using a systems approach to analysis recognizes that food both contributes to and is impacted by key drivers, such as climate change and the broader economy (Rosenzweig *et al.* 2020). Drivers can be categorized into demography and development, consumption, technology, markets, climate and environment, and policy and geopolitics (Zurek *et al.* 2018). Actors include producers, processors, traders, consumers, and others involved in the AFS. Activities include trade, production, storage, postharvest handling, etc. These activities, in turn, are influenced by trends in drivers and by local institutional environments, local support systems, and local norms. The outcomes map to impact areas of GPN but may include other impacts, such as on the environment and on mitigating climate change. Further, the outcomes feed back into the drivers. For example,

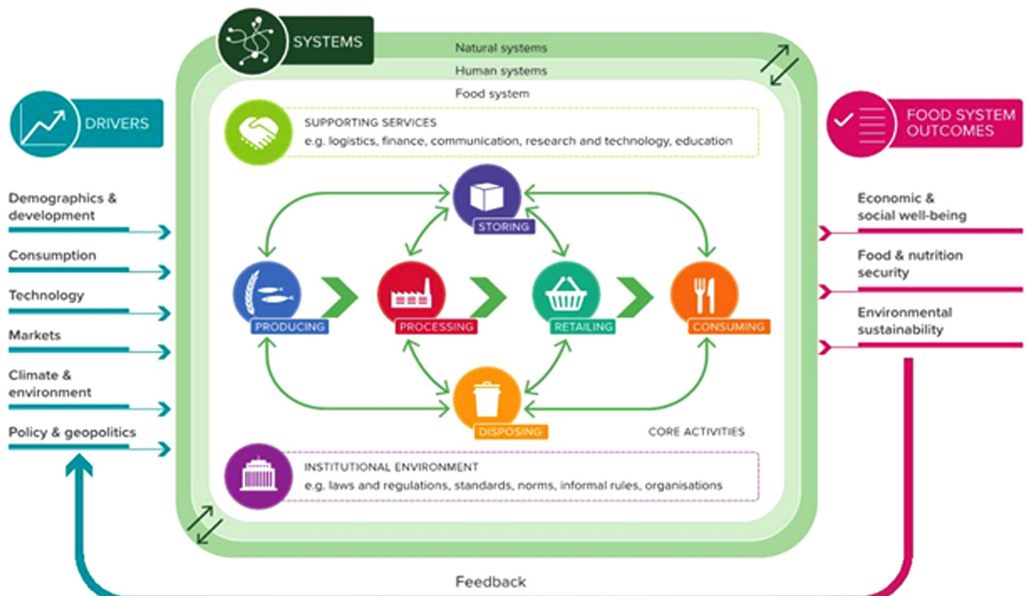

Figure 1. Agri-food system.
Source: Zurek *et al.* (2018).

poverty influences people's consumption decisions, which influences demands for particular agricultural products.

In what follows, I first categorize AFS studies by foresight methodology into three groups: (1) megatrend analysis (what is driving us toward a specific future?); (2) scenario planning (what are likely future worlds?); and (3) visioning and backcasting (how can we reach a certain world?). A megatrend analysis describes how an 'observable phenomenon' is expected to change over a specific time period (in both direction and magnitude: linear, volatile, exponential, etc.) (Wilkinson 2017: 17). Emerging megatrends can often be categorized by driver. Scenario planning results in 'a set of plausible stories of the future' (Wilkinson 2017: 14). Scenarios show how changes to select trends create different futures. The number of scenarios generally ranges between 2 and 6, with each scenario describing both what the future holds and how it may come about. The foresight method of visioning and backcasting starts with a preferred (i.e. normative) future world or future state and then describes pathways useful for attaining that future (Wiebe *et al.* 2018; Wilkinson 2017).

Within each methodology, I then evaluate the studies' impacts on GPN. For each impact area, I assess whether each study's findings present challenges (C), opportunities (O), a mix of the two (M), or uncertainty (U) because consensus is lacking or GPN is not incorporated into the analysis. I identify key findings and areas of consensus and divergence, examine possible implications of the findings for GPN, and describe gaps and limitations. I then identify GPN themes that cut across foresight methodologies. Each foresight methodology has its own summary table of the reviewed studies. I include key information on each study and provide a simple characterization of studies' findings on the impact areas of GPN. For the purpose of this study, the desired impacts are improved gender equality (equity), decreased poverty, and reduced malnutrition in all its forms, with special attention to efforts to enhance diet quality (in contrast to primarily expanding caloric availability).

3 Megatrends

The megatrends presented in Table 1 are divided into common and less common trends, which are then sorted into categories of drivers and their impacts on GPN. Common trends are those that occur with some frequency in the reviewed studies. I split poverty reduction between reductions in poverty for people earning income through the AFS (farmers, processors, traders, transporters, etc.) and for consumers, to reflect that there may be different pathways of impact. For example, lower prices will help impoverished consumers; how they influence small producers' incomes depends on why prices change. In what follows, I synthesize the main megatrends, less common megatrends, and their impact on GPN.

3.1 Major megatrends and their impacts on GPN

The megatrends of climate change and depletion of natural resources are regularly incorporated into megatrend analyses with a consistent direction of change. These drivers all increase pressure on the AFS, primarily by either increasing demand for food or decreasing yields or productivity. There is general agreement that these pressures are unidirectional and often gradual. There is also agreement that such trends will have adverse consequences for GPN: rural producers can expect greater production volatility, consumers can expect increased prices, nutritious foods are likely to be more expensive, the nutrient quality of foods will deteriorate owing to climate change (Myers *et al.* 2014), and women and girls are likely to experience a disproportionate share of these adverse consequences (HLPE 2017).

Two other common trends are population growth and migration, both of which will increase urbanization and likely increase the global middle class. Both trends are likely to increase demand for processed convenience foods, and potentially increase prices. In total, poor consumers are likely to be harmed, and the cost of healthy diets will increase, harming

Table 1. Summary of megatrends and drivers.

		Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)			
	Description of megatrends	Gender equality	Reduce poverty for AFS income earners	Reduce poverty for AFS consumers	Improved nutrition
	Common megatrends				
Climate and environment	*Climate change* may increase volatility of agricultural production, increase pests and diseases, decrease productivity, and increase prices. Climate change can also decrease key nutrients in plants; women may bear a disproportionate burden of absorbing volatility in food access and availability (Myers *et al.* 2014; Willett *et al.* 2019; HLPE 2019; Meenakshi and Webb 2019; Ruane and Rosenzweig 2019; Van der Elst and Williams 2019).	C	C	C	C
Climate and environment	*Depletion of natural resources* may decrease agricultural productivity, harm individuals reliant on biodiverse environments (e.g. indigenous populations), and increase food prices. Water stress may increase the work burden for women in particular, and could contribute to poor health and nutrition outcomes (WEF 2017; Meenakshi and Webb 2019; Van der Elst and Williams 2019).	C	C	C	C
Demography and development	*Increasing migration, urbanization, and increasing global middle class* will likely adversely change diet patterns, with risk of lack of nutritious foods in low-income neighborhoods. In some regions, migration may be gendered and women's off-farm options may be constrained. Migrants also tend to be younger and less risk averse, leaving older, more risk-averse farmers behind who may be less willing to try farming innovations. If structural transformation occurs with out-migration, farming may become more profitable, or rural to urban migration may further increase inequality between rural and urban households (HLPE 2017, 2019; Hazell 2019; Arslan *et al.* 2019; Maggio *et al.* 2019; Meenakshi and Webb 2019; Willett *et al.* 2019).	U	U	O	C
Demography and development	*Population growth and age distribution.* Fertility rates fall faster in urban than rural areas. Some women may face increased caring responsibilities for an aging population and children. Small farmers may split plots into smaller and smaller sizes among their children (Hazell 2019; HLPE 2017).	M	U	U	U
Technology	*Innovations in clean energy* can offset increased demand for natural resources. Several innovative technologies could change AFS, including grid management, green technology, renewable energy, charging stations, ultrahigh-voltage direct current and macro grids, better batteries and more wireless charging, energy trading platforms, zero-carbon natural gas, floating nuclear energy, and subsea power grids.	O	O	O	U
Technology	*Logistics and supply chain innovation* such as automating the supply chain, sustainability in supply chain and logistics, and rebuilding the cold chain may help improve efficiency and/or sustainability in AFS (Future Today Institute 2020).	O	O	O	O

(*Continued*)

Table 1. (*Continued*)

	Description of megatrends	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)			
		Gender equality	Reduce poverty for AFS income earners	Reduce poverty for AFS consumers	Improved nutrition
Technology	*Synthetic biology* aims to redesign organism at a molecular level for new purposes or new environments. *Precision biology* creating 'modern food' could replace other products, such as livestock (RethinkX 2019), but likely has economies of scale, putting it out of reach of small farmers (Huang and Brown 2019). Similarly, *cellular agriculture and insect agriculture* can provide protein sources that are more sustainable (Future Today Institute 2020). Consumer acceptance (HLPE 2017) and whether intellectual property (Graff and Hamdan-Livramento 2019) will be barriers to adoption are open questions.	U	C	O	O
Technology	*Agricultural technologies to decrease unpredictability and risk of production*. Aeroponic growing, vertical farming, indoor plant factories, big data for better produce, precision agriculture, and others can support more controlled growing environments (Future Today Institute 2020). Small farmers are risk averse. Technology companies are getting into agriculture, which could improve food supply but may also squeeze out smaller farmers.	U	U	O	O
Technology	The impact of *AI* will depend on the regulatory environment put in place and how it used (Future Today Institute 2020). AI has the ability to increase the speed of learning (e.g. through deep learning, multitask learning, continuous learning, etc.), which could include identifying ways to increase global food production.	U	U	O	U
Technology	*Accelerating technological change* in areas such as robotics, nanotechnology, photonics, and quantum computing could increase agricultural productivity. Across all technologies, questions of whether new technologies are scale neutral, how they are regulated, and consumer acceptance may ultimately determine whether technologies are adopted (Langridge 2019; Hazell 2019).	U	U	O	O
Consumption	*Shift in consumer preferences* toward Western diet (due to availability of low-cost foods, urbanization, and other factors). Prepared foods could decrease meal preparation by women; convenience and processed foods may increase malnutrition for poor households; small farmers who can access new higher value food change (horticulture and livestock) can benefit from changes in demand; and others will be left behind (Meenakshi and Webb 2019; Willett *et al.* 2019; Hazell 2019).	M	M	C	C
	Less common megatrends				
Climate and environment	*Agricultural pests and diseases* can decrease agricultural productivity (Maggio *et al.* 2019).	C	C	C	C
Climate and environment	*Human disease and pandemics* could disrupt AFS (Serraj *et al.* 2019; NAS 2019).	C	C	C	C

(*Continued*)

Table 1. (*Continued*)

	Description of megatrends	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)			
		Gender equality	Reduce poverty for AFS income earners	Reduce poverty for AFS consumers	Improved nutrition
Climate and environment	*Inadequate water and sanitation*, without improved infrastructure, could harm the AFS (Maggio *et al.* 2019).	C	C	C	C
Climate and environment	*Lack of key fertilizer ingredients* could reduce yields (Maggio *et al.* 2019).	C	C	C	C
Policy and geopolitics	*Decline in public research funding* could slow technological advancement (NAS 2019).	C	C	C	C
Demography and development	*Increasing inequality* between rural and urban residents and between rural farmers as some with access to storage, markets, knowledge, institutions, and technology are able to increase incomes while others' incomes decline or stagnate. This could further fuel (gendered) migration and land extensification (WEF 2017; Hazell 2019; Maggio *et al.* 2019).	C	M	U	C
Consumption	*Sociocultural drivers, cultural traditions, and women's empowerment* (HLPE 2017) shape eating, food purchases, and food environment, policies necessary to promote the right to adequate food (for women and in general) from a sustainable food system beyond measures of access to healthcare and food.	U	U	U	U
Technology, markets, and policy and geopolitics	*Agricultural biotechnology* combined with adequate *intellectual property* can address food security but diffusion may be limited without (1) absorptive power of low income countries (LICs) to commercialize inventions, (2) effective intellectual property regime such that poor countries and poor farmers have access, and (3) public perception of biotechnology (Graff and Hamdan-Livramento 2019).	U	U	U	U
Policy and geopolitics	*Geopolitical dynamics*, including nationalist and isolationist tendencies, are increasing food insecurity (WEF 2017).	C	C	C	C
Policy and geopolitics/markets	*Political and economic drivers* such as leadership, globalization and trade, food, agriculture and nutrition policies, food prices and volatility, land tenure, and conflicts and humanitarian crises influence the AFS. HLPE (2017: 72) points out that leadership may not fully understand the implications of their decisions for impoverished individuals or for power struggles.	U	U	U	U
Technology	*Global food supply technology*, such as artificial trees could sequester carbon; *intelligent packaging* can cut costs and extend shelf life (Hansen *et al.* 2019; Future Today Institute 2020).	O	O	O	O
Policy and geopolitics	*Multi-stakeholder partnerships* (MSPs) (collaborative arrangements between stakeholders from at least two spheres: public, private, and/or civil society) could improve governance at multiple scales in the AFS. However, there are transaction costs, power dynamics, and conflicts of interest that can limit the ability of MSPs to support better AFS governance (HLPE 2018). MSPs (if done well) can foreground approaches that improve outcomes for impoverished and marginalized groups.	O	O	O	O

Notes: Megatrends raised in multiple studies are listed as common; consensus indicates that the direction and magnitude of the megatrend are generally agreed upon. Mixed indicates that the trend is commonly identified, but the expected direction and/or (more commonly) the expected magnitude vary.
A few megatrends are uncommonly included in foresight work (see Maggio *et al.* 2019). Given their somewhat distal impacts on AFS and unclear impacts on GPN, I do not analyze them. These include diversifying approaches to education and learning, the changing security paradigm, the increasing influence of new governance systems, and the expanding influence of the East and Global South.

nutrition (Maggio *et al.* 2019), and overnutrition is likely to increase (Willett *et al.* 2019). The impacts of those two trends on poor farmers and other income earners in the AFS and their impacts on gender are uncertain. While foresight analyses argue that migration will increase, the gender dimension of migration is often neglected (e.g. WEF 2017; Willett *et al.* 2019). Currently, more men migrate than women (HLPE 2017; Arslan *et al.* 2019; Huyer *et al.* 2019), and migrants are generally younger, leaving women and older people in rural areas (Arslan *et al.* 2019). The overall implication of this demographic shift is uncertain. If people migrate to better urban jobs, rural areas may benefit from remittances and/or increased urban demand for food (Arslan *et al.* 2019). A greater share of men migrating may open up income-earning opportunities for women in the AFS, particularly as demand for food increases. However, these opportunities may be undermined by gendered barriers to accessing credit, extension, and information (Quisumbing *et al.* 2019). At the same time, gendered rural-to-urban migration may increase women's on-farm work; as populations age and younger people migrate, women may also face increasing time pressure as they care for both aging relatives and young children. In addition to reducing time available for remunerative activities, women's time poverty may increase demand for convenience foods, with adverse nutritional consequences (Meenakshi and Webb 2019).

The impacts of technological trends on GPN are generally ambiguous. Across foresight research on technology, gender is rarely discussed. Most technologically focused megatrend studies do not discuss requirements to ensure technology adoption by smallholder farmers or by small actors in the AFS. Yet, technology adoption depends on multiple factors including scale neutrality (e.g. technologies captured in the seed, drought-tolerant varietals, or nitrogen-fixing cereals), accessibility across AFS actors, appropriateness to social and ecological context, policies and extension to support equitable adoption, and intellectual property regimes (WEF 2018; Hazell 2019; Langridge 2019; Future Today Institute 2020).

Some technologies could provide opportunities to support improved nutrition and decreased poverty. Scale neutrality makes adoption by poorer farmers more realistic. Technologies with more consistently positive outcomes for poverty include clean and renewable energy and logistics and supply chain innovations, in part because of their scale neutrality (GKI and Rockefeller 2017; WEF 2018). See Table 1 for details on specific technologies such as cold storage and first-mile processing. These can improve efficiency and market access for smallholders, supporting increased and/or more sustainable agricultural production and positive outcomes for poverty and/or nutrition. For example, artificial intelligence (AI), synthetic biology, and a suite of other technologies that can decrease the unpredictability and risk of production could decrease prices and, if used to support the growth of healthier foods, could improve nutrition (Future Today Institute 2020).

Shifts in consumer preferences are ongoing, but the direction and magnitude of these changes are currently ambiguous. In particular, there is substantial disagreement about consumer preferences regarding animal-source foods and whether more people will adopt Western diets that are high in animal-source foods and low in fruits and vegetables. Some studies assume consumers will increase consumption of livestock products (NAS 2019; Maggio *et al.* 2019) and Western diets (Meenashki and Webb 2019; Hazell 2019); others argue that consumers are willing to adapt to consuming lab-based foods and animal products grown using precision biology (RethinkX 2019). Some visioning studies propose policies to nudge or strongly encourage consumers to eat less meat (e.g. Willett *et al.* 2019).

A reason for the lack of consensus about trends in consumer preferences is that studies often have significantly different assumptions about what else will happen in the AFS that may or may not contribute to changing consumer preferences. First, there is disagreement over how transformative synthetic biology will be in the AFS. Several studies argue that synthetic biology could improve food safety, change the way food is produced, and have nutritional benefits (RethinkX 2019; Future Today Institute 2020). RethinkX (2019) argues that synthetic biology will disrupt the AFS, with plant-based foods replacing animal-source

foods and leading to decreased livestock production. The Future Today Institute (2020) identifies meat replacement as just one aspect of innovations in synthetic biology, but it does not discuss changes in consumer demand. Other analyses describe technologies that could support livestock production in its current form (e.g. bio-tattoos) but do not expect systemic changes to livestock production (see NAS 2019). Second, other studies focus on non-technology drivers that may shift consumer preferences. Willett *et al.* (2019) argue for changes to the policy and regulatory environment to expand consumer demand for healthier foods. Maggio *et al.* (2019) argue that income growth and increased urbanization will increase adoption of Western diets. HLPE (2017) argues that a cultural perspective can help explain consumer choices, noting that within some cultures women tend to decide what their households eat. Thus, expected changes in consumer demand turn on whether the studies assume synthetic technology will be a disruptor, on whether policies and regulations that encourage healthy eating will do so, and on the roles of income, urbanization, and culture, among other things.

3.2 Less common megatrends and their impacts on GPN

Several less discussed social, political, and economic trends could also influence the AFS and there is less agreement on the magnitude or direction of these changes (see Table 1). As with the megatrend of shifting consumer preferences, differences in projected outcomes often turn on starting assumptions. Geopolitical dynamics could result in increasing nationalist and isolationist tendencies, which could harm food security and nutrition in low-income or net-food-importing countries (WEF 2017). Changes in political and economic drivers, including increases in conflict and crises, could both disrupt local AFS and put further pressure on AFS, particularly in places with high rates of internal displacement or mass migration (HLPE 2017). Leadership on trade, agricultural, nutritional, and food policies that support a sustainable, healthy AFS could be transformative, as could effective use of multi-stakeholder partnerships to prioritize the needs of marginalized groups (HLPE 2017, 2018). The net result of geopolitical dynamics and political and economic drivers is uncertain.

HLPE (2017) argues that gender relationships and norms are among the most significant drivers of food environments and diets. While a goal in itself, supporting women's empowerment, which includes increasing women's control of household income, expanding women's access to market-based resources, and increasing women's status, could improve nutritional outcomes (HLPE 2017: 79). HLPE argues that several sociocultural drivers, including women's empowerment, play an important role in shaping AFS and the women's futures.

Other less analyzed trends are likely to have adverse impacts on AFS and GPN outcomes by disproportionately harming impoverished individuals, hindering improvements in nutrition, and exacerbating gender inequality. Human disease, inadequate water and sanitation, declines in public funding for agricultural research, failure to address shortages of key fertilizer ingredients (either through changing production systems or through changing inputs), agricultural pests and diseases, and pandemics have the potential to devastate the AFS (Maggio *et al.* 2019; NAS 2019).

3.3 Gaps and limitations

A gap in many of the technology-focused trend studies is the lack of attention on differential adoption. This limits our ability to understand impacts on poverty and gender. New technologies may not be accessible to some farmers or may not be suitable for some environmental or social contexts. Differential adoption rates can impact non-adopting farmers indirectly through prices and can increase disparities between farms in favored versus less favored areas. Without access to extension, credit services, and information, farmers may be unable to adopt new technology or unable to continue using it. Intellectual property rights

can create barriers to adoption, particularly in low-income countries (Graff and Hamdan-Livramento 2019). When technology is not scale neutral, it can contribute to increased inequality between large and small farmers (Hazell 2019). For example, Huang and Brown (2019) point out that while precision agriculture may improve yields and decrease prices in industrial agriculture, it is likely to remain too expensive for most small farmers in the near future.

Gender is generally overlooked in reports focused on technological innovations (e.g. NAS 2019; RethinkX 2019). Rawe *et al.* (2019) point out that women are often not 'recognized as "farmers," so services and technologies are not designed to meet their needs' (p. 23). In addition to addressing the barriers to adoption listed above, gender-equitable technologies prioritize labor savings, particularly for women, are designed with different body types in mind (e.g. smaller plows that women can easily maneuver), and are accessible to women (and other marginalized groups), who may have lower levels of formal education and less formal access to land, and training, credit, extension, and other wraparound services are available, accessible, and targeted to women (Rawe *et al.* 2019; Huyer *et al.* 2019).

Finally, studying trends in isolation can be misleading. Nutrition decisions are complex and the result of food prices, culture and norms, policy environment, and preferences, among others. When one piece of the decision changes, it is uncertain what the overall impact on nutrition will be. For example, the shift in consumer preferences away from animal-source foods may be more transformative for the AFS and for human nutrition if policy changes to discourage meat consumption are paired with an expansion of synthetic biology. At the same time, if more people enter the middle class and strongly associate middle-class lifestyles with eating more meat, the overall impact of synthetic biology on livestock production, without accompanying policy and behavior change, may be muted.

4 Scenarios

Scenarios are intended to show how different assumptions about a set of megatrends and drivers impact outcomes in the AFS. Most of the scenario-based AFS foresight work takes the Shared Socioeconomic Pathways (SSPs) as the departure point for understanding what the AFS looks like in each 'world' (i.e. a scenario with specific assumptions). The SSPs were developed as alternative socioeconomic development pathways to help users better understand and prepare for climate change and its impacts (O'Neill *et al.* 2014). The SSPs do not embed efforts to address climate change or support adaptation, and can thus show different scenarios under which mitigating and/or adapting to climate change is easier or harder (O'Neill *et al.* 2014: 390).

After briefly introducing the SSPs, I analyze three categories of scenarios. The first set of scenarios begins with the SSP Business as Usual (SSP2) as a baseline and then evaluates the impact of more aggressive assumptions about drivers on the AFS (FAO 2018a; Hasegawa *et al.* 2018; FOLU 2019; Willett *et al.* 2019). The second set includes studies that do not use (or do not reference using) SSPs as their baseline (WEF 2017; WRI 2019). The third set of scenarios adapts the set of SSPs to regional specifications (Vervoort *et al.* 2014; Palazzo *et al.* 2014, 2017; Mason D'Croz *et al.* 2016). The line between scenario and visioning foresight work can blur. Both WRI (2019) and Willet *et al.* (2019) discuss several scenarios, and then describe the pathways leading to the preferred scenario outcomes.

Across scenarios, there is general agreement on the need to (sustainably) increase food production, decrease greenhouse gas (GHG) emissions, and address natural resource and land degradation. Many scenarios (e.g. work by the CGIAR Research Program on Climate Change, Agriculture and Food Security, such as Palazzo *et al.* 2014, 2017; Vervoort *et al.* 2014; Mason-D'Croz *et al.* 2016; Hasegawa *et al.* 2018) focus on production outcomes, food prices, and caloric availability as model outcomes rather than on poverty, nutrient quality, and healthy diets. As a result, GPN impacts are often uncertain. Among scenarios that

incorporate a political economy axis (e.g. institutional capacity or regional coordination), worlds with more proactive governance tend to have much better outcomes in terms of food security, growth, and natural resources and land use.

4.1 Overview of the SSPs

The SSPs start with two axes: socioeconomic challenges for mitigation and socioeconomic challenges for adaptation. Four combinations of the axes plus a 'middle' result in the five archetypal scenarios based on the SSPs (O'Neill *et al.* 2014; Riahi *et al.* 2017). The SSPs make assumptions about major socioeconomic drivers. These drivers then inform energy use, land use, and environmental outcomes. Table 2 and the section below provide a brief overview of the SSP scenarios, their axes, and socioeconomic drivers and provide an overview of each SSP world (drawing from O'Neill *et al.* 2014 and Riahi *et al.* 2017). Storyline descriptions of SSP scenarios (drawing from O'Neill *et al.* 2014 and Riahi *et al.* 2017) are as follows:

- *Green Worlds (SSP1)* faces low adaptation and mitigation challenges. Population growth will slow, education will increase, and urbanization could reach 92 per cent. Economic development will be equitable. Renewable energy will increase, land use will be sustainable, and agricultural productivity will be high. Further, diets will be healthy.
- *Business as Usual (SSP2)* is considered to face intermediate adaption and mitigation challenges, including modest extensification for agriculture, slightly lower rates of urbanization, and improvements to education comparable to SSP1.
- *Fragmentation/Regional Rivalry (SSP3)* is driven by high adaptation and high mitigation challenges. High economic growth in some regions increases emissions. Interregional inequality increases, and trade flows decline. Population growth is highest, education levels are stagnant or declining, urbanization is stable, heavy reliance on fossil fuels continues, and land extensification and land pressure increase owing to lack of yield increases and limited environmental protection. Under SSP3, many people are vulnerable to climate change and have low adaptive capacity.
- *Unequal Worlds (SSP4)* has high adaptation and low mitigation challenges. Across scenarios, regional inequality is the highest in this world, leaving some regions economically isolated with high vulnerability and low adaptive capacity. Education levels are stagnant, and land use for agriculture expands modestly. Although there is increased use of renewable energy, it is out of reach for many low-income-country households, who instead rely on biomass.
- *Economy Leads/Fossil Fuels Development (SSP5)* has high economic development and increasing human capital. This results in rapid development and economic convergence, with slower population growth and high rates of urbanization. Climate policies are absent, fossil fuels meet high demands for energy, and there is a modest expansion of land used for agriculture.

GPN outcomes are often not the outcomes scenario developers consider. As a result, the implications of these SSPs for GPN are uncertain, although suggestive. Under SSP3 and SSP4, some regions will have high rates of poverty and slow or stagnant increases in education. Scenarios SSP1, SSP2, and SSP5 will have high levels of education, which can increase human capabilities. Equal access to and participation in education can support gender equality (Rawe *et al.* 2019). Sustainable production is prioritized in SSP1, with a focus on healthy diets. Investments in health are also made in SSP5, although it is unclear whether such investments are related to nutrition.

4.2 Impacts of changing drivers on SSP2 Business as Usual scenario

The majority of SSP-based scenarios start with SSP2 as the baseline scenario. SSP2 faces intermediate adaption and mitigation challenges, including modest extensification for

Table 2. Summary of scenarios.

Worlds within scenario	Axes	World and AFS in it	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)		
			Gender	Poverty	Nutrition
FAO Global Agricultural Perspectives Systems and Environmental Impact and Sustainability Applied General Equilibrium Model to 2050 (FAO 2018a). The SSP2 is the business as usual starting point. Then, FAO uses two economic models: Global Agricultural Perspectives Systems and Environmental Impact and Sustainability Applied General Equilibrium Model to 2050. Three distinct scenarios are characterized by the way the key challenges to food security, nutrition, and sustainability are dealt with: boldly, partially, or not at all. Focus on responses: (1) managing food demand and changing people's dietary preferences (including full costs of food); (2) sustainably address the scarcity and reduced quality of land and water resources; (3) addressing poverty and inequality to achieve food security and nutrition goals; and (4) tackling the nexus between climate change, agricultural sectors, and livelihoods.					
Business as Usual	Middle challenges for food availability and stability and middle challenges for food access and utilization	Global economy grows at moderate rates, with regional disparities and inequalities. Limited investment to increase sustainability of AFS.	C	O	C
Toward Sustainability	Lower challenges for food availability and stability and lower challenges for food access and utilization	Similar growth to SSP2, but more equitable distribution due to proactive policies. Diets shift in high income countries (HIC) and low and middle income countries (LMIC) to more sustainable and less wasteful.	O	M	O
Stratified Societies scenario	Higher challenges for food availability and stability and higher challenges for food access and utilization	Exacerbated income inequalities, with sub-Saharan Africa lagging far behind. Consumption of animal products increases and food waste worsens in HIC. Limited investment in sustainability of AFS and other sectors.	C	M	C
Food and Land Use Coalition (FOLU) SSP2—Global to 2050 (FOLU 2019): Ten assumptions vary between the two scenarios. The Current Trends relies on SSP2 assumptions. The Current Trends scenario shows a food and land use system riddled with inefficiencies and misallocations. The Better Futures scenario makes ten assumptions about productivity, food waste and loss, energy, conversion of land, adoption of healthy diets, sustainable use of ocean resources, and establishment of social protection among others.					
Current Trends (SSP2)		Uses SSP2 Business as Usual as starting point.	C	C	C
Better Futures		The Better Futures scenario makes more aggressive assumptions; underlying such assumptions are sustained political commitment and increased pace of change relative to the Current Trends including increased financing, increased productivity, reduction in food waste and losses, reduction in input overuse, and changes in diets.	O	O	O
Global in 2050 (Hasegawa *et al.* 2018): Consider the impact of ambitious mitigation efforts on SSP2: (1) the carbon tax on agricultural GHG emissions; (2) the carbon tax on the carbon emissions/sequestration associated with land use change; and (3) the carbon tax induces an increase in the biofuel demand from the energy system. Hasegawa *et al.* (2018) start with SSP2 as a benchmark and use a multimodel approach to understand the impacts of climate mitigation efforts on costs of agricultural production and food prices.					
SSP2		Compares eight global agricultural economic models across three dimensions, for a change in temperature in 2100 to be between 2 and 2.7 °C and ambitious mitigation efforts versus no mitigation efforts. While hunger increases consistently, the size of the increase depends on level of warming.	U	C	C

(*Continued*)

Table 2. (*Continued*)

Worlds within scenario	Axes	World and AFS in it	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)		
			Gender	Poverty	Nutrition
Great Food Transformation—Global to 2050 (Willett *et al.* 2019): Start with SSP2 three axes: production (business as usual; improved production practice; improved production practice); food waste (full waste; halve waste); and diet (business as usual, reference, pescatarian, vegetarian, and vegan). Focus on existing or feasible technologies not yet widely implemented.					
SSP2	There are multiple scenarios reflecting that the three axes have multiple outcomes. The reference diet, which stays within Earth's planetary boundaries, was the focal point of the analysis.	Focus is on environmental effects on planetary boundaries of implementing measures considered for reducing the environmental effects of food production. The model considers existing and future projections of food demand, trade, requirements of livestock feed, processing of oilseeds and sugar crops, and non-food demands for agricultural products by industry.	U	U	O
		Scenarios not using SSP			
World Economic Forum—Global to 2030 (WEF 2017): Market connectivity (openness of trade, trust in and resilience of commodity markets, and inclusivity of technological innovations) and demand shifts (nature of the future demand for food and agricultural products: resource intensive versus resource efficient).					
Survival of the Richest (WEF1)	Low connectivity and resource-intensive consumption	Sluggish economy, high inequality, and high environmental cost. In isolated and import-dependent markets, there is increasing hunger and poverty. Population growth, rising inequality, and rising food prices contribute to intensifying use of natural resources, increased migration, and conflict. Technology is not accessible to many people, among other issues.	C	C	C
Unchecked Consumption (WEF2)	High connectivity and resource-intensive consumption	Rapid growth relying on intensive use of resources with serious consequences. Technology focuses on yield improvements; natural resources are further depleted to meet the expanded demand. Global warming is unchecked.	U	M	C
Open-Source Sustainability (WEF3)	High connectivity and resource-efficient consumption	Highly connected markets, resource efficient but may leave some people behind. Trade agreements make provisions for responsible practices. Farmers have access to capital and technology and use resources more efficiently. Consumers demand healthier diets and accept new food products.	U	M	M
Local Is the New Global (WEF4)	Low connectivity and resource-efficient consumption	Fragmented markets with focus on self-sufficiency and appreciate local diets. Shorter food supply chains can help environment, but effects of climatic shocks in disconnected markets can be severe. Comparative advantages among food producing regions are lost and food importing countries may face hunger. Food choices reflect full costs.	U	M	O

(*Continued*)

Table 2. (*Continued*)

Worlds within scenario	Axes	World and AFS in it	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)		
			Gender	Poverty	Nutrition
World Economic Forum scenarios (WEF 2017)—*Emerging markets in 2035* (GKI and Rockefeller 2017): Same as WEF (2017).					
Highlighting impacts of certain innovations for the WEF (2017) scenarios		Ten innovation areas are considered as well as their relevance for each WEF scenario, such as reducing crop failure and spoilage, adopting true cost accounting of food, adopting regenerative agricultural practices, polyculture, and urban agriculture, creating farm-free foods, and addressing data asymmetries and food systems relationships.	O	O	O
World Resources Institute—Global in 2050 (WRI 2019): Uses GlobAgri-WRR model to estimate contribution of twenty-two menu items toward achieving three great needs: addressing food supply, agricultural land area, and GHG emissions. Sustainability criteria include (1) poverty alleviation, (2) empowering women farmers, and (3) protecting freshwater resources. Use the scenarios to understand world outcomes based on the intensity of adoption of the twenty-two menu items. The scenarios are additive and increasing in terms of ambition, coordination, political will, and technology. Some potentially nutritionally beneficial changes, such as decreased animal consumption among those who are overnourished, are described but not explicitly linked to malnutrition in all its forms.					
Baseline		Baseline, using trends as of 2010, assumes business as usual, with lack of coordination. Some productivity gains (per FAO projections) will be made.	U	M	U
Coordinated Effort	Some coordination	Success depends more on strong, coordinated, global commitment to actions that are already well understood, rather than significant advances in technology. Policies are needed to restore land, to protect biodiversity, and to store carbon.	O	O	O
Highly Ambitious	High coordination	Pushes implementing improved technologies, even where they involve higher costs or appear somewhat impractical today. Closes the land gap and potentially makes hundreds of millions of hectares available. Reforesting this land and restoring savannas by mid-century could sequester carbon.	O	O	O
Breakthrough Technologies	High coordination and breakthrough technologies	Builds in levels of achievement that could be realized with significant innovations in and adoption of technologies where there is optimism in that the science is demonstrating progress. Only the Breakthrough Technologies scenario gets close to addressing climate change targets.	O	O	O

(*Continued*)

Table 2. (*Continued*)

Worlds within scenario	Axes	World and AFS in it	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)		
			Gender	Poverty	Nutrition
Regional scenarios: Start with SSPs; use GLOBIOM, IMPACT, and local stakeholder expertise to identify regionally appropriate assumptions for GDP, livestock and crop yields, and production costs and regional axes of interest. Both GLOBIOM and IMPACT incorporate numerous commodities (30 and 62, respectively) in their models. However, most discussion of the impacts of these modeling exercises focuses on food security rather than nutrition. This could just reflect that the prioritization of dietary quality was less a focal point prior to CGIAR One. The reported commodities tend to be staple and livestock.					
SSPs—West Africa in 2050 (CCAFS: Palazzo *et al.* 2014, 2017): Choice of axes is non-state or state actors dominate, and short-term or long-term priorities dominate. These scenarios tend to follow SSPs (indicated in parentheses).					
Self-Determination (SSP1)		Sustainability in investments in productivity and extension services, social programs, regulations to reduce deforestation, and effective social protection schemes. Corruption may increase due to lack of strong institutions, and foreign funding may decrease.	U	O	U
Civil Society to the Rescue? (SSP2)		Weak governments are replaced with strong CSOs tackling food security with a long-term focus, together with strategic investments by a more socially conscious private sector. Modest productivity and commercialization benefits fall to larger farmers. Goals are only partially achieved.	U	M	U
Save Yourself (SSP3)		Action is taken by CSOs in an emergency response manner, and by the private sector acting with short-term profitability interests. Low technology development for the agriculture sector and food security issues due to growing inequality and high population growth. Levels of inequality are similar to SSP4.	U	C	C
Cash, Control, and Calories (SSP5)		A highly urbanized, high economic growth focused scenario, leading to reactive investments in social programs. In contrast to SSP5, investment cycles here are short, creating unstable development.	U	M	U
SSPs—Southeast Asia in 2050 (CCAFS: Palazzo *et al.* 2014; Mason-D'Croz *et al.* 2016): Started with twenty-one plausible surveys, ended with four. Four possible axes: (1) agricultural investment (levels of public and private investments); (2) enforcement capacity and regional collaboration (level of enforcement and level of collaboration); (3) land degradation through land use change (level of degradation); and (4) markets (unregulated, common regulated, and protectionist markets).					
Land of the Golden Mekong	(1) High public and private investment; (2) strong enforcement and regional collaboration; (3) low degradation; and (4) common regulated market	Unification of Southeast Asia on political, economic, and environmental issues gradually becomes a reality. Ultimately, institutions, which are strong and inclusive, can manage the development process, leading to significant improvements in food security, livelihoods, and the environment.	U	O	U

(*Continued*)

Table 2. (*Continued*)

Worlds within scenario	Axes	World and AFS in it	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)		
			Gender	Poverty	Nutrition
Buffalo, Buffalo	(1) Unbalanced, high private investment only; (2) weak enforcement and regional collaboration; (3) high degradation; and (4) unregulated markets	Initially, ASEAN cooperation increases. However, by 2020, corruption weakens national governments. The private sector increasingly acquires land, putting pressure on small shareholder farmers. Food production declines, leading to more migration and societal conflict. By 2050, unsustainable agricultural intensification has led to concentration of agricultural land, a focus on processed foods, and rising inequality.	U	M	C
The Doreki Dragon	(1) Unbalanced, high private investment only; (2) strong enforcement and regional collaboration; (3) high degradation; and (4) common regulated markets	The agriculture sector industrializes through the use of genetically modified organisms (GMO) and other advanced technologies. Large producers dominate at the expense of small shareholders, who become laborers on industrial farms, or migrate to cities. Rapid urbanization and industrialization lead to greater environmental degradation. Highly unequal society, where food security is a major concern in the lower classes.	U	M	U
Tigers on the Train	(1) Low public and private investment; (2) strong enforcement and regional collaboration; (3) low degradation; and (4) protectionist and closed market	Regional collaboration within Southeast Asia increases, but is coupled with increasing protectionism against outside economic influences. High food prices in the near future lead to targeted investments in agriculture, which spur the sector to industrialize with a focus on value-added products. Climate resilience and food security are threatened over time.	U	M	U
SSPs in East Africa in 2030 (CCAFS: Vervoort *et al.* 2014): Two axes: (1) proactive versus reactive governance and (2) fragmented status quo to regional integration. Scenarios focused on dimensions on socioeconomic changes, food security, livelihoods, and environments. Therefore, there is less information on nutrition.					
Industrious Ants	High proactive governance and high regional integration	State and non-state actors are proactive and committed to regionalization with benefits for food security, environments, and livelihoods, but new challenges with corruption and regional push for autonomy.	U	O	U
Herd of Zebra	Reactive governance and low regional integration	Regional integration with a focus mainly on industrialization and economic growth. Little attention is given to food security, environments, and livelihoods until crises occur. Inequality characterizes the region.	U	C	U
Lone Leopards	Proactive governance and low regional integration	Fragmented but proactive governments and non-state actors that achieve scattered though sometimes strong and fast successes; however, region is marked by political and economic instability.	U	M	U

(*Continued*)

Table 2. (*Continued*)

Worlds within scenario	Axes	World and AFS in it	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)		
			Gender	Poverty	Nutrition
Sleeping Lions	Reactive governance and high regional integration	Self-interested governments and non-state actors turning a blind eye or profiting from regional and international exploitation of land and resources leading to unrest but not structural change.	U	C	U
SSPs in South Asia in 2050 (CCAFS: Palazzo *et al.* 2014): The scenarios developed for South Asia considered six factors of change: knowledge, education, and information (human capital); governance and institutions; science, technology, and innovation; political stability and conflict; economic structure; and demographics. Incorporation of assumptions about transfer and availability of technology is the main departure from SSPs. Again, heavy focus on increased availability of products. No discussion of technologies; greater focus on institutions, governance, and trade.					
The New Union of South Asia (SSP1)	(1) High human capital; (2) high governance and institutional capabilities; (3) high transfer and availability of science and technology; (4) high political stability; (5) agricultural sector is not dominant; and (6) low population growth and medium urbanization	Sustainability scenario: Net exporter; in South Asia, crop production increases by nearly 80 per cent for most of the scenarios by 2050. Relative to the 2010 levels, yields are highest for the New Union of South Asia reflecting the high institutional capacity and transfer of technologies for agriculture.	U	O	U
Jugaad (SSP3)	(1) Low human capital; (2) low governance and institutional capabilities; (3) low transfer and availability of science and technology; (4) low political stability; (5) agricultural sector is dominant; and (6) high population growth and high urbanization	In crop production, under Jugaad, the region must import by 2050 due to the growing population and an agricultural sector that faces little innovation and transfer of technology, political instability, and poor governance.	U	U	U
Unstable Flourishing (SSP2)	(1) High human capital; (2) high governance and institutional capabilities; (3) high transfer and availability of science and technology; (4) low political stability; (5) agricultural sector is dominant; and (6) low population growth and medium urbanization	Net exporter; crop yields grow for four of the most produced crops in South Asia: rice, wheat, maize, and sugar. Production is driven by increasing demand for products.	U	O	U
People Power (SSP2)	(1) High human capital; (2) low governance and institutional capabilities; (3) high transfer and availability of science and technology; (4) low political stability; (5) agricultural sector is not dominant; and (6) low population growth and medium urbanization	Net exporter; production is driven by increasing demand for products, and dairy production increases.	U	M	U
Precipice (SSP3 and SSP5)	(1) High human capital; (2) low governance and institutional capabilities; (3) low transfer and availability of science and technology; (4) low political stability; (5) agricultural sector is dominant; and (6) high population growth and high urbanization	Initially a net exporter, but by 2050, Precipice shows signs of a failing agricultural sector and makes only marginal exports of crops.	U	M	U

(*Continued*)

Table 2. (*Continued*)

Worlds within scenario	Axes	World and AFS in it	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)		
			Gender	Poverty	Nutrition
SSPs in Central America in 2050 (CCAFS: Palazzo *et al.* 2014): Institutional capacity, markets, distribution of wealth, and water resources were chosen by stakeholders as the most relevant and uncertain. Demand for monogastrics increases from 2010 to 2050 for all scenarios, due to the expansion of monogastric production and a relative decrease in monogastric meat prices.					
Crowded	(1) Participatory, unregulated markets; (2) medium institutional capacity; (3) inequitable, driven by the state; and (4) high water availability	Second lowest GDP due to growing population and unequal wealth distribution. Food security, measured in available kilocalories per capita per day, increases over the time period. Crop yields improve over the time period.	U	O	U
14 Baktun: the beginning of the Mayan Prophecy	(1) Participatory, regulated markets; (2) high institutional capacity; (3) inequitable, driven by the state; and (4) high water availability	Lower population growth, high GDP growth, and most equitable income distribution. Highest GDP per capita. Crop yields improve over the time period.	U	O	U
Freedom Fighters Without Freedom	(1) Participatory, unregulated markets; (2) low institutional capacity; (3) inequitable, driven by the market; and (4) low water availability	GDP growth is relatively high. Agricultural area, crop areas and grasslands for livestock rearing, expand almost 80 per cent in the region by 2050. To meet this demand for land and expand production, nearly 25 per cent of the forest area is converted and the GHG emissions from this land use conversion are 15 per cent higher than those in the other scenarios.	U	O	U
The New Mayan Collapse	(1) Non-participatory, unregulated markets; (2) medium institutional capacity; (3) inequitable, driven by the markets; and (4) low water availability	Lowest GDP growth, low institutional capacity and poor market conditions, high population growth, decreased investment in agriculture, low increase in caloric availability, and low increase in demand for cereals.	U	O	U
SSPs in Andes in 2050 (CCAFS: Palazzo *et al.* 2014): Concentration of governmental power, markets, consumer preferences, and level of economic development were chosen by stakeholders as the most relevant and uncertain. Food security in the region improves throughout the period for all scenarios.					
Andean Autumn	Centralized political power, unsustainable and unregulated markets with low economic development and subsistence consumption patterns	Low GDP growth and increase in population from 100 to 140 million. Lowest increase in yields; demand for livestock products in this scenario increases by less than 15 per cent, because GDP per capita growth was low.	U	O	U
Flipping Burgers	Decentralized government with unsustainable unregulated markets with high economic growth and sumptuous consumption patterns	Rapid economic growth. The investment in livestock production increases the production of and lowers the price of livestock products, specifically ruminant meat. The amount of calories coming from livestock products increases more than 30 per cent over the time period.	U	O	U
Overcoming Obstacles	Decentralized government with sustainable and regulated markets coupled with high economic development and sustainable needs-based consumption	GDP grows slowly, but then has second highest economic growth by 2050.	U	O	U
New Dawn	Centralized political power, with sustainable regulated markets with a need-based consumption pattern coupled with low economic growth.	Medium population growth (from 100 to 120 million), with low economic growth. Crop yields are highest; lower GPD growth.	U	M	U

agriculture, high rates of urbanization, and improvements to education. Foresight researchers examine how changing assumptions from the SSP2 baseline yield new worlds. Across these SSP2 scenarios, the outcomes of interest vary. FAO (2018a) and Hasegawa *et al.* (2018) focus on prices; how changes in prices influence nutrition and poverty outcomes is discussed in broad terms. In contrast, both FOLU (2019) and Willett *et al.* (2019) assume the world will converge toward a healthy diet and focus primarily on planetary health outcomes, such as land use and rural economic development.

FAO finds that more proactive assumptions relative to SSP2 will have positive AFS outcomes. FAO's most proactive scenario (Toward Sustainability) (FAO 2018a) assumes that global governance can and will induce changes. The specific assumptions include, among other things, that consumer preferences change toward increased consumption of healthier foods, full (true) costing of food is instituted, gender imbalances in access to opportunities are addressed, sustainability of the AFS increases, and climate change slows. These changes are assumed to happen in concert. Findings under this scenario include decreased obesity (due to changes in preferences and true costing of food), decreased poverty (due to expansion of social protection), and improved gender equality (due to proactive gender-equitable policies). When challenges in the AFS are left unaddressed (Stratified Societies scenario), greater gender imbalances, worsening poverty, and increases in all forms of malnutrition will occur, with sub-Saharan Africa expected to fare worst.

FOLU (2019), like FAO (2018a), makes strong assumptions about governance. It starts with SSP2 and then models a Better Futures scenario, which requires sustained political commitment, an ability to address the current inefficiencies and misallocation of resources, and an increased pace of change for positive trends. Outcomes are generally positive and consistent with the more aggressive (and positive) assumptions relative to the baseline of SSP2. FOLU also argues that gender will need to be mainstreamed into efforts to transform the AFS, given pervasive inequalities.

Willett *et al.* (2019) change assumptions about dietary choices (e.g. adoption of a reference diet with little animal-source food and high consumption of pulses and other plant-based foods) and then assess the impacts of these diets on environmental outcomes. The authors start with SSP2 and evaluate a range of values for each of three drivers of the AFS: production, food waste, and diet. They use scenario results to propose pathways to achieving a Great Food Transformation, which would support a worldwide ability to eat the healthy reference diet and stay within planetary boundaries (see Section 5). They propose policy interventions to improve rural infrastructure, expand equitable access to economic resources for women, create social protection programs, and expand knowledge about healthy diets.

Food prices increase in several SSP2-based global scenarios. When price increases are an outcome, most scenario studies highlight adverse consequences for at least some impoverished individuals. Such studies argue that additional policies are necessary to ensure that the poorest and most marginalized are not harmed. FAO (2018a) argues that the impact of price increases on nutrition depends on *which* food prices increase. In their Stratified Societies scenario, for example, the prices of healthier foods are expected to be higher than in other scenarios, contributing to overconsumption. In contrast, using SSP2 as a starting point, Hasegawa *et al.* (2018) focus only on staple foods, which they argue will increase partially due to climate change mitigation efforts.

4.3 Non-SSP scenarios with innovative drivers: global coordination, breakthrough technologies, market connectivity, and food demand

A few studies do not use (or do not reference using) SSPs as their baseline. Regardless, the challenges within the AFS remain the same, as do many of the drivers and assumptions.

Consistent with FOLU (2019), FAO (2018a), and Willett *et al.* (2019), WRI (2019) also uses scenarios to demonstrate a need for stronger global coordination. It is the most technology-forward scenario-based foresight study, seeking to address challenges of food supply, agricultural land area, and GHG emissions. Using its own model, GlobAgri-WRR, WRI identifies twenty-two menu items that additively increase across three scenarios in terms of ambition, coordination, political will, and technology. The most aggressive scenario (Breakthrough Technologies) assumes dramatic improvements in the performance and costs of technologies. Stated goals also include poverty alleviation and empowering women farmers. GlobAgri-WRR does not include feedback from economic changes in its models and identifying the net effect of the bundle of twenty-two interventions on GPN outcomes (WRI 2019: 30) is difficult.

WEF (2017) presents four possible scenarios, which vary by two axes: degree of market connectivity and type of demand for food. WEF's focus on market connectivity and the role of trade is unique among scenarios. Demand for food includes assumptions about the nature of the future demand for food and agricultural products: resource intensive versus resource efficient. Market connectivity includes assumptions about the openness of trade, trust in and resilience of commodity markets, and inclusivity of technological innovations. Within market connectivity, WEF incorporates assumptions about access to technologies (i.e. whether intellectual property barriers will limit technological adoption), a consideration that is also rare in foresight work (although see Graff and Hamdan-Livramento 2019). It also shows how changes in food demand will influence malnutrition. The WEF axis that matters most for smallholder farmers and most for addressing malnutrition is whether resources are efficiently or intensively used (on the demand for food axis). Greater connectivity is more beneficial for GPN outcomes when added on top of resource-efficient use. GKI and Rockefeller (2017) used the WEF (2017) scenarios to point out that certain interventions will have greater impacts on certain of the four WEF worlds, whereas other interventions transcend worlds.

4.4 Regional scenarios building off of the SSPs

CGIAR's Climate Change, Agriculture and Food Security (CCAFS) team worked with stakeholders from six regions to adapt the SSPs to region-specific scenarios to 2050. Regional specifications include choice of axes and regionally specific assumptions about GDP per capita, crop and livestock yields, and production costs. Every regional scenario includes at least one regional political economy—focused axis. Several regions focused on governance and institution capacity (East Africa, West Africa, South Asia, Andes, Central America). Regions also considered the degree of regional economic integration, regional market regulation, and collaboration (East Africa, Southeast Asia, Andes). Other axes focus on land use, consumer preferences, water resources, and human capital, among other things. The outcomes primarily discussed are yield gaps (with some attention to land extensification) and food security (Palazzo *et al.* 2014).

Consistent across the regional scenarios, more proactive governance improves food security outcomes (see Table 3). Also consistent with other scenarios, weak regional collaboration paired with resource degradation, unregulated markets, and unbalanced investment yields the most inequality and highest likelihood of increased hunger. Across these regional scenarios, because the focus is on yields of staple crops, growth in GDP, and staple food prices, the nutritional outcomes are uncertain. Decreases in food prices might benefit hungry consumers but could also lead to overnutrition, depending on how consumer preferences change (e.g. if more people adopt Western diets). Several studies identify increases in food insecurity, which could hinder nutrition and have gender-differentiated intrahousehold impacts. However, gender and nutrition are not explicitly discussed in the CCAFS scenarios, making impacts on them uncertain.

Table 3. Summary of the SSPs.

	SSP1: Green World/Sustainability	SSP2: Business as Usual	SSP3: Regional Rivalry	SSP4: Inequality	SSP5: Economy Leads/Fossil-Fueled Development
Axes	Low adaptation and mitigation challenges	Moderate challenges	High adaptation and high mitigation challenges	High adaptation and low mitigation challenges	Low adaptation and high mitigation challenges
World and AFS in it	Sustainable development: decreased inequality; technological change is rapid and directed toward environmentally friendly processes	Intermediate case between Green World and Regional Rivalry	Unmitigated emissions are high due to economic growth, increased population, and slow technological change in the energy sector. Inequality is high across regions, decreasing trade flows, leaving many people vulnerable to climate change and with low adaptive capacity.	Technological development in low-carbon energy sources, leading to large mitigative capacity in regions with high emissions. Yet, regional inequality is high, leaving some parts of the world economically isolated with high vulnerability and low adaptive capacity.	In the absence of climate policies, energy demand is high and met with carbon-based fuels. Economic development is high and human capital increases, which produces a higher distribution of resources, slower population growth, and a world better able to adapt to climate impacts.
Socioeconomic drivers					
Population	Population growth will slow (7 billion by 2100), decreasing demand for food		Population growth is highest in SSP3, reaching 12.6 billion		Population growth will slow (7 billion by 2100), decreasing demand for food

(*Continued*)

Table 3. (*Continued*)

	SSP1: Green World/Sustainability	SSP2: Business as Usual	SSP3: Regional Rivalry	SSP4: Inequality	SSP5: Economy Leads/Fossil-Fueled Development
Education	Education increases, with important implications for economic growth and vulnerability to climate change impacts	Education increases, with important implications for economic growth and vulnerability to climate change impacts	Education level is stagnant or even declines	Education level is stagnant or even declines	Education increases, with important implications for economic growth and vulnerability to climate change impacts
Urbanization	Highest urbanization rates (92 per cent by 2100) due to high income growth, and desired increases in efficiency that compact urban areas can bring	Urbanization increases to 80 per cent in 2100	Stable urbanization (60 per cent by 2100) due to low economic growth, limited regional mobility, and poor urban planning	Highest urbanization rates (92 per cent by 2100)	Highest urbanization rates (92 per cent by 2100) due to technological change and large-scale engineering projects to develop housing
Economic development	Equitable development and rapid catch-up/economic convergence		Development failure with strong fragmentation, and economic stagnation, with relatively high inequality	Highest levels of cross-national inequality, with high fragmentation	Very rapid development and economic convergence

(*Continued*)

Table 3. (*Continued*)

	SSP1: Green World/Sustainability	SSP2: Business as Usual	SSP3: Regional Rivalry	SSP4: Inequality	SSP5: Economy Leads/Fossil-Fueled Development
Adaptation scenarios					
Energy	Increased use of renewables		Fossil fuels and lack of policies to address energy access, resulting in increased use of biomass by households in LICs	Increased use of renewables and lack of access for LIC households, resulting in increased use of biomass	Fossil fuels
Land use	Sustainable land transformation with low population growth, healthy diets, and high agricultural productivity	Low to modest expansion of land use	Large pressure on land due to expansion of cropland and pasture land due to increased population and lack of increase in agricultural productivity and limited environmental protections	Modest expansion of land use	Modest expansion of land use

The SSPs are used to evaluate socioeconomic challenges for climate change adaptation and mitigation measures. Main socioeconomic drivers of the SSPs are population, education, urbanization, and economic development (O'Neill *et al.* 2014; Riahi *et al.* 2017).

4.5 Gaps and limitations in scenarios

First, future work on the specific challenges within sub-Saharan Africa could be valuable. Several global scenarios identify sub-Saharan Africa's AFS to be at greatest risk (FAO 2018a; WRI 2019; Willet *et al.* 2019). Regional scenarios (Palazzo *et al.* 2014) concur, showing East and West Africa most sensitive to deteriorating conditions in the AFS and likely to experience food insecurity.

Second, the reliance of most foresight scenario work on SSPs as starting points may be limiting. While they offer a consistent departure point for understanding the influence of socioeconomic drivers on the AFS, given the dominance of the SSPs there is a decreased possibility of radically different findings across studies. Scenarios that start with SSP2 as the baseline are assuming that SSP2 is the right or most realistic departure point. If other scenarios are more accurate, for example those with high rates of urbanization (SSP1, SSP4, and SSP5), increases in food prices may adversely impact more (urban) residents than currently expected. This could have important implications for urban poverty levels, particularly if other sorts of poverty alleviation measures are not in place.

Third, all scenario builders make choices about which types of trends to focus on. Most scenarios include gradual megatrends rather than shocks or acute one-off events that could ripple through the global economy. Human diseases and pandemics (e.g. COVID-19) and agricultural pests and diseases (e.g. the 2019–20 desert locust infestation in East Africa) are not included in either visioning or scenarios. Scenario building does not include unseen technologies and often cannot pick up feedbacks (Hasegawa *et al.* 2018). The scenarios reviewed exclude a few megatrends that could be pertinent for understanding GPN outcomes, such as changes to water and sanitation (Palazzo *et al.* 2014; FAO 2018b; Maggio *et al.* 2019; WRI 2019). Indirect impacts of climate change, such as increased heat stress or changes to nutrient content of some foods (e.g. Myers *et al.* 2014), are rarely included. These concerns may be secondary; however, incorporating them may allow for a richer understanding of the impacts of AFS transformations on GPN.

Fourth, few scenario outcomes map directly to GPN outcomes. For example, food price change is a commonly considered scenario outcome. However, we should be wary about assuming increases in food prices is a proxy indicator for increases in poverty and deteriorations in nutrition. First, the net effects of price changes differ across AFS actors. Price increases will likely harm poor consumers but may or may not harm other AFS actors. If staples are Giffen goods, staple price increases would increase consumption of those staples. Dietary quality may fall, increasing malnutrition and potentially impoverishing purchasers, but net sellers of Giffen goods may experience a drop in poverty. Second, price changes will likely not occur in a vacuum. If policies to nudge consumer preferences are successful, adverse impacts of price changes on nutritional outcomes could be mitigated. Finally, some work (e.g. Palazzo *et al.* 2014; Hasegawa *et al.* 2018) looks at price changes for 'food', meaning staples. However, relative prices of different foods will change if, for example, polyculture techniques are widely adopted or if postharvest losses (PHL) in horticulture decrease. Decreasing the relative prices of fruits and vegetables could support adoption of healthier diets, even if staple prices rise. Willett *et al.* (2019) argue that adopting full costing of food could support improved nutritional outcomes by changing the relative prices of foods. In sum, a better understanding of how the interactions of prices, economic growth, climate change mitigation policies, and changes in inequality, among other things, may combine to improve or worsen GPN outcomes is needed.

Finally, GPN outcomes are infrequently incorporated into the reviewed scenarios. When they are, strong assumptions about the efficacy of global or regional governance appear to be the dominant drivers in achieving positive GPN outcomes. Scenarios that do incorporate GPN outcomes often assume coordinated global governance, which may be a strong assumption. In these scenarios, GPN outcomes are often achieved by decreasing the cost

of healthy foods (e.g. horticultural products) relative to unhealthy foods (e.g. diets high in staples and livestock products), as well as expanding social protection and pursuing low-inequality growth to protect impoverished individuals.

5 Visioning and backcasting

Visioning studies provide responses to *a* future rather than providing foresight into *possible or plausible* futures. Several reports first propose specific visions of the future, such as 'sustainably feed 10 billion people in 2050' or 'meet the SDGs, sustainably'. Then, the reports propose pathways that can help us to arrive at that future. The pathways are often composed of bundles of technologies and/or policies. The visioning studies depart from the megatrend analyses and scenario analyses because they often explicitly include the objectives of poverty alleviation, improved nutrition and health outcomes, and/or gender equality in their desired world.

Nearly all visioning studies assume that a similar set of megatrends will impact the AFS. The megatrends include (1) climate change, (2) decreasing natural resources, environmental degradation, and increasing demand for agricultural land, and (3) increased demand for food and shifting preferences. Thus, the perceived need for the future AFS generally is to identify pathways to *sustainably* increase *healthy* food production. While there is general agreement on the key challenges, different studies weight specific concerns or objectives more or less heavily; these weights inform their proposed pathway (see Table 4). For example, NAS (2019) focuses more on sustainability, efficiency, and resilience of the AFS with less focus on GPN. WRI (2019) considers water-related challenges and, like Quisimbing *et al.* (2019), the role of gender in the AFS. WEF (2018) and FOLU (2019) explicitly incorporate inclusivity.

These areas of emphasis also inform the approaches proposed to achieve the proposed pathways. The pathways are often a blend of components, such as sustainable agriculture techniques, natural resource conservation, technologies, markets, businesses, nudges in consumer choice, government coordination, and regulations. Each study weighs the transformative value of various pathway components differently and tends to highlight their preferred dominant component(s). The weights placed on each component reflect authors' implicit and explicit assumptions about what is required to achieve a sustainable, healthy food system. For example, GKI and Rockefeller (2017), WEF (2018), and Hansen *et al.* (2019) recognize the need for supportive policies but focus on technology to drive change in the AFS. A few studies focus more narrowly on 'scientific breakthroughs' and do not consider issues of technological access, adoption, or regulation (NAS 2019).

In what follows, I split pathways by common themes, including environmentally driven pathways to sustainable agriculture and conservation, technology-driven pathways, policy-led and integrated pathways, and the roles of markets and true costing. I then discuss gaps and limitations.

5.1 Environmentally driven pathways to support sustainable agriculture and conservation

Many studies envision farmers moving toward more sustainable farming techniques. Such techniques could mitigate the current contributions of the AFS to environmental degradation and climate change and make farming less reliant on unsustainable inputs and land extensification. The proposed farming approaches include ecological intensification, which results in nutrition-sensitive landscapes (Tittonell 2019); efforts to improve soils, including conservation agriculture and low-till agriculture (WRI 2019); agroecological and other transformative approaches (HLPE 2019); a shift toward a bioeconomy (Birner and Pray 2019); redesigned agricultural systems that take an integrated approach to improving

Table 4. Summary of visioning and backcasting.

Pathway	Proposed response	Impact on AFS and GPN	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)			
			Gender equality	Reduce poverty for AFS income earners	Reduce poverty for consumers	Improved nutrition
Anderson (2019): *To support farm-focused R&D and reduce poverty and hunger.*						
Markets	Reduce trade restrictions	Reduce trade restrictions and decrease farm subsidies	O	O	O	O
Birner and Pray (2019): *To achieve SDGs, sustainably by 2050.*						
Integrated	Bioeconomy	The bioeconomy approach aims to improve the economic system by using bio-resources and biotechnologies, and focusing on the provision of environmental services (Birner and Pray 2019: 503)	U	O	O	U
FOLU (2019): *By 2030, food and land use systems can help bring climate change under control, safeguard biological diversity, ensure healthier diets for all, drastically improve food security, and create more inclusive rural economies.*						
Integrated	Nutritious foods	Global diets need to converge toward local variations of the 'human and planetary healthy diet'—a predominantly plant-based diet that includes more protective foods (fruits, vegetables, and whole grains), a diverse protein supply, and reduced consumption of sugar, salt, and highly processed foods. Affordable healthy food could improve nutrition and decrease poverty—but requires transformation of tax policy, agricultural subsidies, targeted investment and innovation, and behavior change. Women may benefit more from convergence toward a healthy diet as they are at greater risk of undernutrition.	O/U	O	O	O
Climate and environment	Nature-based solutions	Pursue productive and regenerative agriculture; protecting and restoring nature; and a healthy and productive ocean. Relying on external inputs creates risk for some small farmers; decreasing deforestation cuts down on air pollution and other health costs may disproportionately affect the poorest; biodiversity loss also undermines the stewardship of indigenous peoples, which tends to outperform other forms of stewardship (FOLU 2019: 97–8). Ocean farming of bivalves could substantially increase and remain within planetary boundaries, which could be an alternative protein source. Regenerative agriculture may be better at improving soil health, which can deliver more nutrients to food crops (FOLU 2019: 79).	O/U	O	O	O

(*Continued*)

Table 4. (*Continued*)

Pathway	Proposed response	Impact on AFS and GPN	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)			
			Gender equality	Reduce poverty for AFS income earners	Reduce poverty for consumers	Improved nutrition
Integrated	Wider choice and supply	Diversifying protein supply; reducing food loss and waste; local loops and linkages. Increasing the supply of affordable proteins will contribute to human nutrition and health, with particular benefits for child and maternal health in poorer households. Alternative meats might be most beneficial for poorer residents. Decreasing waste and local production may increase the availability of fresh foods and help address malnutrition in urban and peri-urban areas. However, intellectual property rights for meat alternatives may make the costs of these proteins (e.g. farmed insects) too high (p. 121). Livestock farmers may be at risk. Expanding local supply reduces risks of over-reliance on staple foods. Reducing food loss could make more nutrients available, improving nutritional outcomes but require progressive policies and scaling and strengthening efficient local value chains.	O	U	O/U	O
Integrated	Increase rural opportunities	Digital revolution; stronger rural livelihoods; gender and demography. Non-farm opportunities for rural youth and rural women often have lower returns than for older men, given lack of initial and access to resources, smaller scale, and sectoral foci. Use policy to ensure the rights of women and girls, expanding access to reproductive health services. While digitization could improve efficiency of smallholders, the costs of and probability of them being left behind are both substantial. Expanding rural education, access to health, improved infrastructure, insurance, and off-farm employment opportunities could decrease poverty and increase nutritional status. Digitization can help consumers make healthier and safer food choices.	M	M	O	O

(*Continued*)

Table 4. (*Continued*)

Pathway	Proposed response	Impact on AFS and GPN	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)			
			Gender equality	Reduce poverty for AFS income earners	Reduce poverty for consumers	Improved nutrition
GKI and Rockefeller Foundation (2017): *In face of environmental degradation, climate change, urban opportunities and rural decline, hidden costs in global supply chains, and private sector influence, how can we transform food systems in emerging markets by 2035?*						
Technology	Farmgate packaging and processing	Farmgate or near-farmgate packaging, processing, (pre)cooling, and dehydration could decrease food waste and increase smallholders' incomes. Smallholder income may increase through premium on packaged products. Increasing commercialization of some productive activity (e.g. horticulture) may not benefit women if these value chains do not reward women's labor. Extended shelf life can help retain nutrients and decrease prices.	O/U	O	O	O
Technology	Renewable energy	Renewable energy can support energy-intensive operations such as cold storage and processing. Can be used for refrigeration and processing, helping farmers earn premiums on their products. Can indirectly impact nutrition by decreasing prices of fresh foods.	O/U	O	O	O
Technology	Storage and transport	The suitability of innovations in storage and transport technologies for foods that have a short shelf life varies by farm size. Storage crates, micro-cold transport, and evaporative cooling can help link smallholders to higher value chains. Adaptable reefer containers, cold chain as a service, and micro-warehousing and shipping may be useful for smallholders if prices are low enough and if agribusinesses work with smallholders. All can potentially increase the availability and decrease the cost of nutrient-rich foods.	O/U	O	O	O
Technology	Life sciences	Biodegradable coatings, microbiomes/microbes for soil could reduce PHL; they could also be applied on-seed in place of herbicides and pesticides. Can reduce PHL, particularly if affordable and accessible to smallholders. Can lower prices of nutrient-rich foods. Need for food safety standards, e.g. biodegradable coatings often require access to clean water and could cause illnesses if clean water is not available.	O/U	O	O	O/U

(*Continued*)

Table 4. (*Continued*)

Pathway	Proposed response	Impact on AFS and GPN	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)			
			Gender equality	Reduce poverty for AFS income earners	Reduce poverty for consumers	Improved nutrition
Technology	Data collection and monitoring	Early warning systems to identify risks of PHL. Could decrease smallholders' PHL and decrease price volatility. Requires strong government or firm institutional commitments to effectively communicate findings to farmers.	O/U	O/U	O	O
Integrated	Enabling innovations	Improved traceability, specialty marketing of crops, farm-to-fork virtual marketplace, first loss capital guarantee for PHL, mobile education centers, and behavioral economics for agriculture. If appropriate institutions are in place, decrease PHL and/or increase smallholder income; could decrease prices of nutrient-rich foods. Barriers to such opportunities may vary by gender.	O/U	O	O	O
Hansen *et al.* (2019): *To sustainably address malnutrition in emerging markets, focus on twelve new ideas and new technologies that could be ready to be scaled and impactful in the next 5 years. In all cases, the primary beneficiaries of the deployment of these innovations would be the poor (or at a minimum, those on modest incomes) in low- and middle-income countries. These twelve technologies can be bucketed into four priorities: (1) start with sustainable, nutritious foods; (2) invest in proximate processing; (3) tackle traceability for safety and transparency; and (4) keep it cool.*						
Technology	Sustainable nutritious foods	Production, processing, and consumption of sustainable local foods reduce long-term reliance on imports and can yield planetary and human health benefits, including millet-based foods.	O/U	O	O	O
Technology	Invest in proximate processing	Processing and value addition closer to the point of production reduces PHL, ensures nutrient retention, and increases the volume of nutritious foods on the market, including (1) cooperative processing and packaging, (2) low-cost solar dryers, (3) mobile pre-cooling and packhouses, (4) modular factories, and (5) near-farm mobile processing.	O/U	O	O	O
Technology	Tackle traceability for safety and transparency	Efficient and transparent distribution enables access to wider markets, stabilizing demand, and reducing price volatility, while ensuring food safety, including (1) value-added traceability, (2) market brokerage via mobile devices, and (3) on-demand third-party logistics. Can decrease price volatility and stabilize demand, beneficial for smallholders and consumers.	O/U	O	O	O

(*Continued*)

Table 4. (*Continued*)

Pathway	Proposed response	Impact on AFS and GPN	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)			
			Gender equality	Reduce poverty for AFS income earners	Reduce poverty for consumers	Improved nutrition
Technology	Keep it cool	Cold storage options at the last mile extend the life of nutritious food and make more nutrients available to vulnerable rural populations such as mothers, children, and adolescent girls, including (1) small-scale refrigerated transport, (2) small-scale cooling boxes, and (3) solar cooling.	O	O	O	O
HLPE (2017): *Progressive realization to the right to adequate food and nutrition and aim to transform the food system to ensure sustainable diets that are protective and respectful of biodiversity and ecosystems; culturally acceptable; accessible; economically fair and affordable; and nutritionally adequate, safe, and healthy, while optimizing natural and human resources (pp. 11–2). HLPE argues that lack of recognition of rights, unaddressed power imbalances, and conflicts of interest are all barriers to changes in the food system.*						
Integrated	Production systems	Improve landscape and dietary diversity; safeguard globally important agricultural heritage systems in traditional and mixed food systems; incentivize protection of wild foods and agrobiodiversity; improve links between farms and schools; promote urban agriculture; improve women producers' livelihoods; redirect agricultural R&D toward diets; scale up climate-smart, nutrition-sensitive interventions.	O	O	O	O
Technology	Storage and distribution	Reduce loss and waste; preserve and improve food safety.	O	O	O	O
Technology	Processing and packaging	Promote ways to protect and add nutritional value in the food chain; facilitate fortification as appropriate; regulate food processing.	O	O	O	O
Markets	Retail and markets	Improve connectivity of smallholders to markets; encourage supermarkets to procure healthier foods; support farmer connectivity through IT.	O/U	O	O	O
Integrated	Evidence gaps in food supply chain	Need better methods; smallholder farms do not exist in isolation—need to consider several spatial scales; farmers face trade-offs; biodiversity trade-offs; small and medium enterprises (SME) may face specific challenges (pp. 92–3).	U	U	U	U
Policy and geopolitics	Availability and physical access	Address food deserts and food swamps; encourage healthier diets via public procurement of healthy food.	O	O	O	O

(*Continued*)

Table 4. (*Continued*)

Pathway	Proposed response	Impact on AFS and GPN	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)			
			Gender equality	Reduce poverty for AFS income earners	Reduce poverty for consumers	Improved nutrition
Policy and geopolitics	Economic access	Promote healthier diets through discriminatory trade policies; encourage healthier diets through taxation and subsidies; promote healthier diets through price promotions; understand remittances.	U	U	O	O
Policy and geopolitics	Promotion, advertising, and information	Promote healthier foods; strengthen regulations for advertising; increase transparency of labeling.	O	O	O	O
Policy and geopolitics	Food quality and safety	Certify food safety across all food systems; improve quality across all systems.	O	O	O	O
Consumption	Evidence gaps in food environment	Document the extent of changes in food environments in different contexts and the specific role of certain drivers (Kimenju and Qaim 2016). Second, effects of different aspects and drivers of the nutrition transition on diets and nutrition may differ by context and age group, and may involve several trade-offs, and by the effect of complex and dynamic drivers, such as trade and globalization, on diets (Thow *et al*. 2010). The third stream of research could investigate how to influence the food environment to supply healthier food products (HLPE 2017: 100).	U	U	U	U
Consumption	Nutrition education	Strengthen nutrition education; use mass media and social communication to encourage consumer behavior change; develop food-based guidelines for healthy and sustainable diets; ensure social protection programs lead to improved nutrition outcomes.	O	O	O	O
Consumption	Food acceptability	Change aesthetic standards to decrease food loss and waste.	O	O	O	O
Consumption	Social norms and tradition	Promote traditional food cultures to improve health and nutritional status; promote traditional food preparation skills.	O	O	O	O

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Table 4. (*Continued*)

Pathway	Proposed response	Impact on AFS and GPN	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)			
			Gender equality	Reduce poverty for AFS income earners	Reduce poverty for consumers	Improved nutrition
Consumption	Evidence gaps in consumer behavior	'Further research is needed to better understand consumer behaviour and demand, as well as the determinants of that demand now and in the future (Cirera and Masset, 2010; Godfray *et al.*, 2010). A second stream of research is needed on measuring affordability, convenience and desirability from the consumer's perspective. The third stream of research will be on understanding how policies can influence consumer choice and diets in this era of changing food environments, particularly in LMIC settings.' (HLPE 2017: 106).	U	U	U	U
Policy and geopolitics	Investments in interventions	One approach to prioritizing investment is to consider the global food system to consist of three main subtypes of systems, including a traditional system, a mixed system, and a modern system. The types of interventions needed (e.g. food safety) will vary by food system subtype.	O	O	O	O
HLPE (2019): *To address Agenda 2030, '… the HLPE explores the nature and potential contributions of agroecological and other innovative approaches to formulating transitions towards sustainable food systems (SFSs) that enhance FSN …. Many transitions need to occur in particular production systems and across the food value chain to achieve major transformation of whole food systems.'* (HLPE 2019: 13). *SFSs 'ensure food security and nutrition for all in such a way that the economic, social and environmental bases to generate food security and nutrition of future generations are not compromised.' …. Several controversies about conventional and agroecological agriculture remain.*						
Climate and environment	Incremental sustainable intensification of production systems	Incremental movement toward climate-smart agriculture, nutrition-sensitive agriculture, and sustainable food value chains that reduce inputs, foster diversity, and focus on improving ecological and human health and addresses equity and governance issues while increasing productivity per unit of land (p. 15).	O	O	U	O
Climate and environment	Transformative agroecological and related approaches	Transformative changes including organic agriculture, agroforestry, and permaculture may contribute to access and utilization dimensions and to social equity. However, these approaches may not increase productivity per unit of land (p. 16).	O	O	U	O

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Table 4. (*Continued*)

Pathway	Proposed response	Impact on AFS and GPN	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)			
			Gender equality	Reduce poverty for AFS income earners	Reduce poverty for consumers	Improved nutrition
Technology	Farm size	Controversy: There is an increasing recognition that economies of scale in agriculture are context dependent and vary with the extent to which environmental and social externalities are factored into performance measurement metrics (p. 16).	U	U	U	U
Technology	Modern biotech	Controversy: Despite substantial uptake of gene modification (GM) technology, debates continue to be polarized with public concerns about safety, environmental impacts, concentration of power within food systems, and the ethics of gene modification (p. 17).	U	U	U	U
Technology	Digital technologies	Controversy: Digital technologies, if more widely adopted, could, according to sustainable intensification proponents, contribute to improve the sustainability of food systems. Proponents of agroecological approaches emphasize a need to focus on democratic governance, agency, and knowledge systems, to scrutinize *what* is being attempted through the use of digital technologies, *by whom*, and *what kinds* of future food systems are being fostered through their application (p. 17).	U	U	U	U
Technology	Synthetic inputs	Controversy: The viability of different strategies for maintaining soil fertility in high-yielding agricultural practices is highly context dependent, in relation to soil type, the nature of the farming system, and what sources of fertilizer are locally available (p. 17).	U	U	U	U
Technology	Biofortification	Controversy: Growing diverse crops versus biofortification. The two strategies can be integrated with producers and consumers being offered informed choices about adopting biofortified crops, diversified production, or both (p. 17).	U	U	U	U
Technology	Biodiversity	Controversy: Conserving biodiversity within agricultural landscapes to meet conservation goals versus maximizing land for conservation while maximizing yield on agricultural land. There is growing consensus that the overall impact of agriculture on insect and other biodiversity is reaching alarming proportions that exceed planetary boundaries (p. 18).	U	U	U	U

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Table 4. (*Continued*)

Pathway	Proposed response	Impact on AFS and GPN	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)			
			Gender equality	Reduce poverty for AFS income earners	Reduce poverty for consumers	Improved nutrition
Policy and geopolitics	Performance measures and monitoring frameworks	Comprehensive performance metrics, covering all the impacts of agriculture and food systems, are a key requirement for rational decision-making (p. 19).	O	O	O	O
Integrated	Transition toward diversified and resilient food systems	Redirect subsidies to support farms based on sustainability performance metrics; recognize true cost accounting; refine ecological footprint accounting to capture regenerative practices; reduce food loss; take greater steps to integrate local and scientific knowledge; call for public investment in R&D in pulses, fruits and vegetables, and orphan crops (p. 19).	O	O	U	O
Policy and geopolitics/demography and development	Agency and empowerment	Agroecology initiatives that advocate for women's formal rights are essential. These ensure land access, more equitable family and community relationships, and reorientation of institutions and organizations to explicitly address gender inequality. This latter inequality is a key barrier to transitions to SFS in many contexts. … Addressing gender inequality requires recognition of (1) women's central roles in agriculture and food systems and (ii) the often high labor demands in holistic agricultural management systems, making greater income equality for those providing important labor (p. 20).	O	O	U	O
Policy and geopolitics	Need for effective policy	Risk of relying on the market to motivate movement toward SFS. Government policy, regulation, and moves toward true pricing aim at internalizing all ecological and social effects of production in the price of food, enabling markets to function in ways that would foster transitions toward SFSs (p. 18).	O	O	U	O

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Table 4. (*Continued*)

Pathway	Proposed response	Impact on AFS and GPN	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)			
			Gender equality	Reduce poverty for AFS income earners	Reduce poverty for consumers	Improved nutrition
National Academies Sciences (2019): *To achieve efficiency, resilience, and sustainability of AFS (p. 29) in the context of increasing and changing demand, environmental degradation, and climate change.*						
Technology	Transdisciplinary science and systems approach	Transdisciplinary science and systems approaches should be prioritized in AFS research.	U	U	O	U
Technology	Biosensors and new sensing technologies	Field-deployable sensors and biosensors will enable rapid detection and monitoring capabilities across various food and agricultural disciplines. Biosensors could decrease PHL, increase productivity, and decrease prices. Unclear whether it will reach smallholders.	U	U	O	O
Technology	Data science, AI	Facilitate the adoption and development of information technology, data science, and AI in food and agricultural research. Unclear whether it will reach smallholders.	U	U	O	O
Technology	Gene editing	Gene editing will allow for precise and rapid improvement of traits important for productivity and quality. Could be used to improve nutritional qualities of foods; could assist smallholders reduce use of synthetic inputs and curtail antibiotic resistance.	O/U	O/U	O	O/U
Technology	Microbiome	Understand microbiome and harness knowledge to improve crop production, transform feed efficiency, and increase resilience to stress and disease. May decrease pests and improvements in microbiome may increase nutrient availability.	O/U	O/U	O	O
Pingali and Aiyar (2019): *To support food, agriculture, and nutrition in 2050, given demand challenges (increasing population, increasingly urbanized, changing consumption patterns) and supply challenges (climate change).*						
Integrated	Integrated food systems approach	Shift from sector-specific goals to integrated, climate-sensitive agriculture systems and shift from caloric production toward nutritious foods. Address both gender discrimination and barriers women face and address barriers to technology adoption to support smallholders.	O	O	O	O

(*Continued*)

Table 4. (*Continued*)

Pathway	Proposed response	Impact on AFS and GPN	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)			
			Gender equality	Reduce poverty for AFS income earners	Reduce poverty for consumers	Improved nutrition
Quisumbing *et al.* (2019) (ReSAKSS): *Attention to gender is required to achieving inclusive agricultural growth (through 2025).*						
Policy and geopolitics/ demography and development	Achieve greater gender equity	Achieving a gender transformative food system would require a focus on four key elements of gender equality that have been addressed in this report, but in combination—increasing access to control over productive resources, investing in women's leadership, addressing gender and social norms, and removing structural and institutional barriers. The latter two strategies—addressing gender and social norms and removing structural and institutional barriers—are less common in the agriculture sector, yet they are the most fundamental to creating a gender transformative food system (Quisumbing *et al.* 2019: 211).	O	O	O	O
Rawe *et al.* (2019): *Feeding and nourishing a growing and changing global population in the face of rising numbers of chronically hungry people, slow progress on malnutrition, environmental degradation, systemic inequality, and the dire projections of climate change demands a transformation in global food systems.*						
Climate and environment	Reduce GHG emissions	Numerous policies include mitigation and adaptation to climate change, extension services to address equity and equality issues, financial or market mechanisms like subsidies or payment for ecosystem services, carbon prices, good governance, and level playing field. Land tenure is a prerequisite to incentivize the adoption of practices that can not only reduce emissions and increase resilience but also improve the health (and value) of land. Nutrient-dense foods should be prioritized for production. Women face systemic inequality within the food systems and bear a disproportionate labor burden in the AFS. Policies should support extension to small farmers and women farmers rather than subsidies to large farmers. Systemic inequalities make marginalized households most at risk of climate stress.	O	O	O	O
Integrated	Tackle food loss and waste	Measures for tackling food waste can be 1) information-based, 2) market-based,3) regulatory, 4) voluntary commitment, and 5) 'nudging' (p. 17).	O	O	O	O

(*Continued*)

Table 4. (*Continued*)

Pathway	Proposed response	Impact on AFS and GPN	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)			
			Gender equality	Reduce poverty for AFS income earners	Reduce poverty for consumers	Improved nutrition
Consumption	Shift diets	Food systems policies that address diets and the environments can target (1) the food environment to help consumers make healthy choices through dietary guidelines to promote sustainable diets and (2) the food supply to increase production of diverse, nutrient-rich foods, to support farmers to diversify production, and to climate-proof infrastructure and transportation. Gender equality must be prioritized.	O	O	O	O
Schwoob *et al.* (2019): *To achieve SDGs by 2050.*						
Climate and environment	Redesign agricultural systems	Agronomy-centered farming system transformation aimed at improving environmental performance and agricultural system's socioeconomic performance. Need for national-level work.	U	M	C	O
Skeer and Leme (2019): *To support efforts to keep global warming below 2 °C by 2050.*						
Climate and environment	Renewable energy and bioenergy	There has been a rapid uptake of renewable energy. If yield gap in agriculture closes, opportunity to grow bioenergy crops on degraded lands, which could benefit marginalized farmers; if done carelessly, this could increase GHG emissions.	U	O	O	O
Tittonell (2019): *To feed 9 billion people nutritious food, decrease poverty, increase sustainability, and work within planetary boundaries by 2050.*						
Climate and environment	Ecological intensification	Ecological intensification decouples agriculture from nonrenewable resources, improves soil health, integrates crop and livestock, ecological intensive smallholder agriculture, and focuses on nutrition-sensitive agriculture and ecological management.	U	U	C	O
WEF (2018): *To feed 10 billion people and meet SDGs by 2050 requires a global food system that is inclusive, sustainable, efficient, and nutritious and healthy. The Fourth Industrial Revolution can disrupt current food system technology. Three main categories of technological innovation are required: (1) change the shape of demand; (2) promote value chain linkages; and (3) create effective production systems. Also required is creating an enabling environment for technological development as well as investing in basic infrastructure and regulatory policy. Moving toward full cost accounting, recognizing that interventions are complementary and more likely to be effective when bundled, including when bundled with health, education, and environmental innovations (p. 31).*						
Technology/ consumption	Change the shape of demand	Technologies including alternative proteins, food-sensing technologies for food safety, quality, and traceability, and nutrigenetics have the potential to shape consumer diets and consumption behaviors. Consumer acceptance of and health implications of alternative proteins are still unclear. Adoption of some technologies (food sensing and nutrigenetics) may be in HICs first; ultimately nutrigenetics may decrease obesity.	O/U	O/U	O	O/U

(*Continued*)

Table 4. (*Continued*)

Pathway	Proposed response	Impact on AFS and GPN	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)			
			Gender equality	Reduce poverty for AFS income earners	Reduce poverty for consumers	Improved nutrition
Technology/markets	Promote value chain linkages	Technologies including digital infrastructure and mobile technologies, big data and advanced analytics for insurance, internet of things for real-time supply chain transparency and traceability, and blockchain-enabled traceability can impact value chains via improved collaboration, simplified efficient supply chains, and transparency. Improved traceability technology and blockchain for traceability could provide consumers more information on the nutritional quality of foods but will need to be widely adopted by farmers. Insurance could reduce farmers' risk; mobile technologies could improve efficiencies. Low literacy may limit farmers' (perhaps especially women's) abilities to use some of these technologies.	O/U	O/U	O	O
Technology	Create effective production systems	Technologies include precision agriculture for input and water use optimization, gene editing for multi-trait seed improvements, microbiome technologies to enhance crop resilience, biological-based crop protection and micronutrients for soil management, and off-grid renewable energy generation and storage for access to electricity could help to sustainably produce the right quantity and quality of food to meet the nutrition demands of the world. Gene and microbiome technologies could significantly decrease waste, increase production, and increase farmers' income. However, there could be differential adoption, leaving smallholder farmers behind. Some technologies must be developed for specific locations and consumers need to be willing to accept them. The use of biological-based crop nutrients could improve the health and safety of farmers who would no longer apply dangerous herbicides and pesticides; food safety would also be improved. Gene editing could improve nutrient content of foods. The nutritional impacts of microbiome technologies are unclear.	U	U	O	O/U

(*Continued*)

Table 4. (*Continued*)

Pathway	Proposed response	Impact on AFS and GPN	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)			
			Gender equality	Reduce poverty for AFS income earners	Reduce poverty for consumers	Improved nutrition
Willett *et al.* (2019): *EAT–Lancet proposes a reference diet (composition varies by region) that remains within Earth's planetary boundaries ('safe operating space for food systems'). The reference diet (2500 kcal/day) would require a 50 per cent reduction in global consumption of unhealthy foods and a 100 per cent increase in consumption of healthy foods. Willet et al. (2019) also includes scenarios. See scenario summaries as well.*						
Consumption	International and national commitment to shift toward healthy diets	Wide variety of proposals, which vary by region, country income status, and urban–rural needs within countries (e.g. expanding transportation, public distribution programs, contracts and procurement for food in schools, role of education and dietary guidelines, portion control, etc.). Other policies are broadly applicable such as food prices should reflect true costs. Poverty alleviation, particularly for women, is crucial for securing healthy diets from sustainable food systems. Attends to the specific nutritional needs of women and girls. Dietary changes from current diets to healthy diets are likely to substantially benefit human health. Hirvonen *et al.* (2020) have computed affordability and cost of the proposed reference diet. They argue that without a combination of higher income, lower prices, and nutritional assistance, the cost of the reference diet will exceed household per capita income for an estimated 1.58 billion people.	O	O	M	O
Integrated	Reorient agricultural production from large quantities of food to healthy food	Need for better tools to track diet quality; incentives to produce nutritious plant-based foods may be useful, as well as decreasing animal production. Some areas will continue to produce meat; these areas may be already marginalized (e.g. ASAL regions) and, if meat is no longer demanded, could harm small (as well as large) livestock producers.	O/U	U	U	O
Climate change and environment/technology	Sustainably intensify food production, generating high-quality output	Mixture of technological innovations (precision agriculture), agroecological techniques (cover crops), and biodiversity conservation. Technologies vary by whether they are scale neutral and labor intensive. Variable impact on small farmers, possibly gender equity, and prices. Given the focus on biodiversity conservation, it may be that sustainable intensification does not decrease prices.	M	M	U	O

(*Continued*)

Table 4. (*Continued*)

Pathway	Proposed response	Impact on AFS and GPN	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)			
			Gender equality	Reduce poverty for AFS income earners	Reduce poverty for consumers	Improved nutrition
Policy and geopolitics	Strong and coordinated governance of land and oceans	Need for effective governance and collective action, including restoration of degraded land. Regionally specific. May be that conservation and restoration techniques benefit indigenous groups; some farmers without formal holdings may lose access to land.	U	M	O	O
Integrated	At least halve food loss and waste, in line with global SDGs	Steep reductions in food loss and waste will require cooperation among multiple actors in the food system to assess sources of food loss and waste and develop targeted solutions. Because of the high involvement of women in postharvest handling (as well as many other activities), these services should be designed to engage with and be accessed by women producers in developing countries (p. 482).	U	O	O	O
World Resources Institute (2019): *Focus on technical opportunities and policies for cost-effective scenarios to meet food, land use, and GHG emissions goals in 2050 in ways that can also help to alleviate poverty and do not exacerbate water challenges. An additional sustainability criterion is empowering women farmers (p. 31). WRI (2019) is also considered a scenario. See scenario summary as well.*						
Consumption	Reduce growth in demand for food and other agricultural products	(1) Reduce food loss and waste; (2) shift to healthier and more sustainable diet; (3) avoid competition from bioenergy for food crops and land; and (4) achieve replacement-level fertility rates. To decrease fertility, pursue education of girls, increase access to reproductive healthcare, and decrease maternal and infant mortality. All of these would also increase the well-being of women in general. Increasing production via advances in molecular biology and breeding technologies could improve productivity. They could also leave out smallholders, depending on costs and intellectual property.	O	U	O	O

(*Continued*)

Table 4. (*Continued*)

Pathway	Proposed response	Impact on AFS and GPN	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)			
			Gender equality	Reduce poverty for AFS income earners	Reduce poverty for consumers	Improved nutrition
Climate change and environment/technology	Increase food production without expanding agricultural land	(1) Increase livestock and pasture productivity; (2) improve crop breeding to boost yields; (3) improve soil and water management; (4) plant existing cropland more frequently; and (5) adapt to climate change. Adoption may be limited, reflecting high (gendered) labor inputs. Some farmers may be too small to adopt these technologies, and policies are needed to help small farmers access markets and off-farm income. The authors warn that producing pulses and higher nutrient-dense foods (e.g. fruits and vegetables) may take more land per calorie than the staple grains that are currently used in animal feeds.	O/U	O/U	O	O/U
Policy and geopolitics	Protect and restore natural ecosystems and limit agricultural sand shifting	(1) Link productivity gains with protection of natural ecosystems; (2) limit inevitable agricultural expansion to lands with low environmental opportunity costs; (3) reforest abandoned, unproductive, and liberated agricultural lands; and (4) conserve and restore peatlands. If marginalized or indigenous populations rely on forest resources, more protection of those resources could leave them worse off.	O/U	O/U	U	U
Integrated	Increase fish supply	(1) Improve wild fisheries management and (2) improve productivity and environmental performance of aquaculture. More research is needed to develop fish oil substitutes from microalgae, macroalgae (seaweeds), or oil seeds for aquaculture feeds.	O/U	O	O	U
Technology	Reduce GHG emissions from agricultural production	(1) Reduce enteric fermentation through new technologies; (2) reduce emissions through improved manure management; (3) reduce emissions from manure left on pasture; (4) reduce emissions from fertilizers by increasing nitrogen use efficiency; (5) adopt emissions-reducing rice management and varieties; (6) increase agricultural energy efficiency and shift to non-fossil energy sources; and (7) focus on realistic options to sequester carbon in agricultural soils. The benefits of these technologies turn on their accessibility, intellectual property (IP), and labor requirements.	O/U	O/U	U	O

(*Continued*)

Table 4. (*Continued*)

Pathway	Proposed response	Impact on AFS and GPN	Potential impact on GPN outcomes (U = uncertain; O = opportunity; C = challenge; M = mixed)			
			Gender equality	Reduce poverty for AFS income earners	Reduce poverty for consumers	Improved nutrition
Policy and geopolitics	Cross-cutting policies for a sustainable food future	(1) Farm structures, large land acquisitions, property rights, and contractual arrangements; (2) carbon-pricing strategies and financing of climate-smart agriculture; and (3) strengthening research and development. Addressing land rights using a gender lens (e.g. ensuring women have the right to inherit land) can support sustainable intensification of land. Smallholders will be disadvantaged when participating in carbon offset programs because the transactions costs are so high. Large-scale land acquisitions ('land grabs') should occur in places with relatively low environmental opportunity costs and in countries where crop expansion is inevitable.	O/U	O	U	U

environmental and socioeconomic outcomes (Schwoob *et al.* 2019); and an integrated climate-sensitive AFS that includes nutritious foods (Pingali and Aiyar 2019). These techniques generally prioritize growing a greater diversity of products, which can benefit nutrition (Pingali and Aiyar 2019; Tittonell 2019). HLPE (2019) argues for a two-pronged strategy including both transformative (e.g. organic, permaculture, and agroforestry) and incremental (e.g. nutrition-sensitive and climate-smart) shifts in agricultural production systems. Which techniques are adopted and by whom could vary across sizes and types of production systems and ecological contexts. Such changes could decrease the yield volatility small farmers experience and potentially increase access to nutritious foods (Tittonell 2019; Pingali and Aiyar 2019; HLPE 2019). However, productivity per unit of land may not increase (HLPE 2019).

The labor requirements for such holistic agricultural approaches are generally, although not always, higher than other agricultural techniques, which may hinder gender equity (HLPE 2019). Improving soil and water management, if done with low-barrier technologies (e.g. water harvesting), could save women and their families time and physical effort (WRI 2019). However, as WRI (2019) notes, many soil-improving and soil-conserving techniques require increased inputs, increased labor, or both, which have limited their adoption to date. Access to land may also constrain adoption of holistic agricultural approaches by small farmers such as formalization of land sales and rental markets and support for farmers transitioning out of farming (WRI 2019). A further limiting factor is women's lack of formal land rights and loss of usufruct land rights, particularly in sub-Saharan Africa (HLPE 2019; WRI 2019).

5.2 Technology-driven pathways

Several reports argue for technology-driven transformations of the AFS. Yet, few of the technology-driven visions address how to ensure or whether these technologies will be accessible to and useful for women, smallholders, and other AFS actors. Which technologies are adopted and by whom turn on several factors: scale neutrality; governance regimes (e.g. intellectual property rights); the presence of complementary infrastructure, extension, and credit services; the costs and risks of adoption; user acceptance; whether the technologies are labor saving; and whether technologies need to be tailored to specific locations (Langridge 2019; Hazell 2019).

In the contemporary AFS, examples of low adoption rates of technologies are commonplace. Tittonell (2019) examines the opportunity for ecological intensification to decrease the smallholder productivity gap in sub-Saharan Africa, arguing that many modern agricultural technologies 'were not developed to fit the reality of smallholder systems' in sub-Saharan Africa and that this failure contributes to their low adoption rates and smallholders' continued low relative productivity (p. 466). Similarly, the role of gender in agronomic, market, and consumption decisions influences the likelihood of adoption of technologies (e.g. biofortification) that may support nutrition (Quisumbing *et al.* 2019). Training men on planting and women on nutrition may be less effective than outreach strategies that target both men and women (Doss and Quisumbing 2019). When technologies increase income or marketing opportunities for certain agricultural products, women may also lose decision-making power over them (GKI and Rockefeller 2017; Quisumbing *et al.* 2019).

Several scale-neutral or small-scale technologies are poised to offer potential benefits to smallholders, other AFS actors, and/or consumers and therefore may face lower barriers to adoption. Scale-neutral innovations include farmgate packaging and processing technologies such as mobile precooling and packhouses; dehydration and cooling technologies such as solar driers, solar cooling, and evaporative cooling; cooperative processing and packaging and near-farm mobile processing; and storage and transport technologies such as storage crates and micro-cold transport (GKI and Rockefeller 2017; Hansen *et al.* 2019). Improved and institutionalized data collection, improved traceability, farmer connectivity to markets

through information technology, and market brokerage services could be made accessible to small actors in the AFS (GKI and Rockefeller 2017; HLPE 2017; Hansen *et al.* 2019). Renewable energy can support farmgate packaging and processing as well as cold storage transportation along the AFS, including for the last mile (GKI and Rockefeller 2017; Skeer and Leme 2019). Innovations in life sciences such as biodegradable coatings (with food safety regulations) and microbiomes and microbes for soil could reduce food waste and PHL. In sum, these technologies could increase efficiency across the AFS and provide opportunities for farmers to earn premiums on their products or to decrease PHL. They also will likely expand the availability of nutritious foods and decrease food waste along the AFS. Several of these also support increasing production of safer, healthier foods, benefiting nutrition. However, Huyer *et al.* (2019) warn that there are considerable gender gaps in digital agricultural services and mobile finance. Therefore, while scale-neutral technologies could benefit some smallholders, gender-based barriers to adoption make the gender impacts uncertain.

Other technologies have the potential to be transformative for the AFS but may be less accessible to smaller actors and whether they will positively impact gender and poverty is uncertain. Some could support improved nutrition. Biosensors and food-sensing technologies could decrease PHL and increase productivity (WEF 2018; NAS 2019). They, along with blockchain technologies, could also support traceability, transparency, and safety in the AFS (WEF 2018). Synthetic biology, including gene editing, and microbiome technology could increase crop yields, increase resilience to stress and disease, and even increase nutrient availability (WEF 2018; NAS 2019). WEF (2018) notes that gene-editing and microbiome technologies could have substantial benefits for famers but that intellectual property issues must be resolved. Data science and AI can support improvements in and hasten research on crop breeding (NAS 2019) and aid in pricing of insurance (WEF 2018). WEF (2018) argues that while biological-based crop protection could save costs, decrease input use, and increase food safety, the technology needs to be tailored for specific locations, potentially limiting its uptake in low-income countries. Similarly, precision agriculture, nutrigenetics, and food-sensing technologies are likelier to be adopted in Western AFS first (WEF 2018; Huang and Brown 2019). Questions about consumer acceptance of biological-based crop production, biotechnology for plant-based meat alternatives, synthetic biology, and gene editing remain, which makes their impact on nutrition uncertain (WEF 2018; HLPE 2019; FOLU 2019; Serraj *et al.* 2019).

HLPE (2019) is more cautious about the role of technology in the AFS, arguing that there are several unresolved debates about transformative technologies and management techniques in agriculture, including farm sizes, modern biotechnology, digital technologies, synthetic fertilizers, the role of biofortification, and biodiversity. Such calls for more cautious approaches to technology are often part of pathways that prioritize strong governance and leadership.

5.3 Policy-led and integrated approaches

Several visioning exercises propose transformation of the AFS. These studies tend to argue that current AFS faces multiple externalities and governance failures that cannot be addressed through technology or markets alone. The studies take the position that while pathways ought to include new technology, sustainable environmental approaches, and market-led changes, a critical requirement for AFS transformation is effective global and local policies and regulations.

HLPE (2017, 2018, 2019), Rawe *et al.* (2019), and Willett *et al.* (2019) advocate for strong leadership from government and for policies and regulations integrated with science and technology. In its 2019 study, HLPE warns that market actors have little incentive to address systemic externalities associated with agricultural production and processing. Rawe

et al. (2019) warn, 'Without effective policy coordination, there could be actors working at cross purposes, elite capture, and entrenchment of poverty and inequality' (p. 11). Some aspects of the global AFS require multilevel coordination in policymaking. For example, three studies (WRI 2019; FOLU 2019; HLPE 2019) detail how business as usual regarding oceans and ocean-based foods is unsustainable and will remain so without coordinated governance.

Integrated interventions interact in multiple ways, making it difficult to discern the net effects of holistic, cross-sectoral combinations of interventions on GPN. In one example, Willett *et al.* (2019) advocate for a bundled approach to achieve a Great Food Transformation. This would require a global reorientation toward healthy diets and away from an AFS focused on producing calories. Sustainable intensification, technologies, conservation, poverty alleviation, changing consumer demand, and the true costing of food (among others) will support this goal. Yet, Hirvonen *et al.* (2020) assessed the cost of the reference diet proposed by Willett *et al.* (2019), finding that without a combination of higher incomes, lower prices, and nutritional assistance, the reference diet's cost will exceed household per capita income for an estimated 1.58 billion people. Thus, while the Great Food Transformation seeks to improve nutrition, conclusions about the degree to which greater attention to poverty is required vary. Similarly, WRI (2019) argues for a holistic approach to building a sustainable and healthy food system that will also empower women (among other outcomes); it offers twenty-two menu items that can support this transformation. Yet, the net effect of these menu items, either alone or in combination, on any specific GPN goal is uncertain. For example, WRI proposes to expand access to reproductive healthcare and to pursue soil and water management techniques. While reproductive healthcare will support women, conservation agriculture techniques with high labor requirements that are not accompanied by changing norms may disproportionately increase women's work burden.

5.4 Markets and full costing

Several studies raise the issue of full (true) costing (see FAO 2018a; WEF 2018; FOLU 2019; HLPE 2019; Willet *et al.* 2019) and the role of agricultural subsidies (WRI 2019; Anderson 2019) in their scenarios or visioning. FOLU (2019), for example, argues that incentives in the AFS must change in order to better incentivize businesses to pursue strategies aligned with healthier and sustainable food systems and that people need to be 'paid fairly to produce the right food the right way' (p. 17). HLPE (2019) argues for true costing, 'There are many externalities associated with production, processing and distribution of food that are not priced and … agri-food input and retail sector often works against addressing these externalities' (p. 18). FAO (2018a) argues that true costs will reduce overconsumption in high-income countries. Full costing of labor and full income measures that incorporate leisure (Quisumbing *et al.* 2019) might change the relative payoffs to particular strategies and could make visible the work that women do within the AFS.

Accomplishing such market transformations would require sustained policy efforts (HLPE 2019). Full costing is likely beneficial for smallholders within the AFS, but is also likely to increase consumer prices, potentially increasing the costs of healthy diets (FAO 2018a; HLPE 2019). Several studies argue that tackling food waste, creating nutrition-sensitive social protection programming, incorporating consumer subsidies, and/or providing nutritionally sensitive social protection (see FAO 2018a) will dampen the impacts of higher prices on poor households. Such a bundled approach would require coordinated, high-level policy.

5.5 Gaps and limitations

First, visioning exercises show us pathways to idealized futures and often include little discussion of whether the assumptions are plausible. For example, it is often assumed that

technologies beneficial to the AFS will be adopted, but, in reality, there are often numerous barriers to adoption. Similarly, it is also often assumed that it is possible to achieve effective, coordinated global policy.

Second, there is little discussion of how different innovations within a study interact with one another or whether trade-offs across impact areas will be necessary. The interactions of drivers could increase or decrease the likelihood that these visions are achievable. For example, moving to the full costing of food may make regenerative agricultural practices more appealing. Thus, there is a need for coordination across seemingly disparate aspects of the AFS to ensure that, as Rawe *et al.* (2019) point out, efforts are not at cross-purposes and, ideally, are complementary.

Finally, even addressing single issues within the food system may need interventions that draw on coordinated efforts (HLPE 2019). For example, reducing food waste may require an integrated pathway combining regulation, markets, technologies, and communication. Rawe *et al.* (2019) lay out a variety of policy-based approaches, including nudges, regulation, and information campaigns. GKI and Rockefeller (2017) propose technologies to reduce waste such as increasing shelf life of food through cooling and proximate processing (see also Hansen *et al.* 2019). Willett *et al.* (2019) argue that because women are heavily involved in postharvest processing in low-income countries, food waste solutions should be accessible to and informed by women producers. It is unclear whether, in combination, these approaches will be multiplicative, additive, duplicative, or work at cross-purposes. Visioning studies that lay out clearly the assumptions of each intervention and how they interact with one another could help policymakers assess the implications of various pathways for GPN—and other—outcomes.

6 Opportunities for practitioners, policymakers, donors, and others

Based on the megatrends, scenarios, and visioning, several themes emerge. First, most of the studies show that to support healthy diets, the AFS needs to move away from increasing cereal yields and focus on expanding production of horticultural crops. Second, while there is some disagreement on the mix of changing agricultural management practices and changing agricultural technologies, there is agreement that the AFS needs transformations in both. If designed with small AFS actors in mind, innovations such as supply chain logistics and packaging can be pro-poor, support increased access to nutritious foods, and decrease food waste. Third, based on CCAFS scenarios (see Palazzo *et al.* 2014), the greatest food security needs (a rough proxy for poverty) will remain in sub-Saharan Africa, and possibly South Asia. Additional themes are discussed in greater detail below.

6.1 Evaluating technologies' and innovations' possible impacts on GPN

Analyses related to GPN are generally missing from current AFS foresight work. There are notable exceptions, including CGIAR-led work (e.g. Huyer *et al.* 2019; Quisumbing *et al.* 2019). Mainstreaming of GPN concerns throughout the AFS will improve understanding and increase the likelihood of desired outcomes being achieved. A critical area for future research is developing methods and approaches to identify whether and when GPN outcomes will be furthered by innovations, technologies, and management techniques. For example, numerous foresight studies propose technological interventions to support a transformation of the AFS; few, however, systematically consider well-established barriers to adoption.

Consumer acceptance, regulatory environment, economies of scale, access to credit and other supportive infrastructure, adaptation to regional social and environmental needs, and labor requirements are some of the considerations that may determine the uptake of new technologies (WEF 2017; NAS 2019; Hazell 2019; HLPE 2019; Quisumbing *et al.* 2019; Tittonell 2019). Some foresight authors are more critical of technology-led innovation in

agriculture, citing concerns that technology is treated as a straightforward mechanism for change and arguing instead for development of inclusive and participatory innovations (HLPE 2019). Careful, participatory analysis of barriers to adoption that takes a gendered, pro-poor, and nutrition-focused lens could help address these concerns.

6.2 Clarifying interactions, trade-offs, synergies, and sequencing

There is a need to systematically and explicitly map the relationships between intermediate outcomes and GPN outcomes as well as the trade-offs across different impact areas. Such a mapping will aid in the analysis of the net effects of AFS transformations on GPN and is needed for two reasons.

First, we have a poor understanding of the net effects of multiple efforts to transform the AFS on GPN. Many studies proposing transformations to the AFS do not focus on GPN or draw uncertain conclusions about GPN based on intermediate outcomes such as prices and crop production. These intermediate outcomes may interact with other drivers, or multiple drivers may interact with each other. These interactions are left unspecified because realistic assumptions are hard to identify (e.g. WRI 2019). However, such interactions could offset or compound impacts on GPN outcomes.

Second, well-informed leadership will be critical for transformation of the AFS. HLPE (2017) argues that the quality of leadership is the key requirement for AFS transformation (see also FOLU 2019; HLPE 2019; Rawe *et al.* 2019; Willett *et al.* 2019; WRI 2019). A multisectoral and multilevel coordinated approach to policymaking can address inevitable trade-offs and harmonize policies and incentives (Rawe *et al.* 2019). However, leaders may not fully understand the complex implications of policy decisions for impoverished individuals, for inequality, or for other outcomes (HLPE 2017; Rawe *et al.* 2019). There is a need for development practitioners, researchers, and others to support effective, coordinated leadership by not only making trade-offs visible to policymakers, but also incorporating the perspectives of multiple stakeholders to inform decisions regarding trade-offs (HLPE 2018).

One reason for the difficulty in understanding the net effects on GPN is that trends and innovations can be synergistic or involve trade-offs, and/or they may require sequential roll-out. Visioning studies describe bundling, sequencing, and menu-based approaches in their recommendations, and such approaches are helpful for understanding impacts on GPN. When interventions are interlinked, implementing them simultaneously can produce virtuous cycles (FOLU 2019). Approaches that are menu based allow for local and regional choices (WRI 2019). However, careful sequencing of interventions may make sense; for example, low-income countries may not benefit from big data analytics in agriculture without addressing basic infrastructure needs first (GKI and Rockefeller 2017). Simultaneous interventions may be required when individuals face multiple barriers (e.g. interventions in agricultural finance, inputs, and access to value chains could be bundled; Quisumbing *et al.* 2019) and can help protect the most marginalized.

6.3 Recommendations for future foresight work

A challenge of inferring findings from foresight work to the impact areas of GPN is much of the foresight work reviewed here was undertaken with other goals in mind and GPN outcomes are often not included. Addressing the following gaps could help develop future foresight studies that assess GPN outcomes.

First, biotic pressures on the AFS and resulting from climate change were not commonly included in the reviewed foresight studies and are rarely linked to GPN outcomes. Human disease, heat stress on labor productivity, the physiology of plants and nutrients, inadequate water and sanitation, shortages of key fertilizer ingredients (either through changing production systems or through changing inputs), agricultural pests and diseases, and pandemics have the potential to devastate the AFS (Myers *et al.* 2014; Maggio *et al.* 2019; NAS 2019).

These concerns may be secondary; however, incorporating them may allow for a richer understanding of the impacts of AFS transformations on GPN.

Second, the most common megatrends are gradual changes rather than shocks or acute one-off events (e.g. pandemics) that could ripple through the global economy or regional AFS (e.g. desert locusts in East Africa). Some disruptive technologies (e.g. AI or synthetic biology) seem poised to change the AFS in high-income countries. While some authors identify such technologies as relevant primarily for high-income countries, they will likely spill over either directly or indirectly into low- and middle-income countries. For example, synthetic biology could decrease demand for livestock in the United States, leading to decreased demand for staple crops used for livestock feed and potentially depressing global staple food prices. The implications of such spillovers for GPN are not described or well understood.

Third, there are several challenges with using food prices as an outcome, and greater clarity is needed about the impact of price changes on GPN outcomes and about how prices interact within the food system. The net effects of price changes will differ: by AFS actors, by whether 'food' means staples or a diverse and nutritious diet, by changes in relative prices of different foods, by other changes within the AFS, and by whether there is a movement toward the full (true) cost of food. Decision-makers and policymakers need a better understanding of how prices, economic growth, climate change mitigation policies, and changes in inequality, among other things, may interact to improve or worsen GPN outcomes.

Finally, the visioning work often makes strong assumptions about possible pathways to desired futures. Two commonly made assumptions are that there are no or few barriers to adopting new technologies and management practices and that multilevel policy coordination with strong global governance will occur. The pathways detailed may not be realistic when these assumptions do not hold. Clarifying the impact of these assumptions on envisioned pathways and identifying ways to support these assumptions may make such pathways more achievable.

7 Conclusion: GPN themes and the future of AFS foresight studies

Most foresight studies warn that the future, without significant transformations, will be challenging for many actors within the AFS. Some foresight studies warn that, if left on its current path, the AFS will face serious challenges, including adverse nutritional outcomes and stalled progress on (or increases in) poverty and gender inequality. Other studies do not consider GPN outcomes. Thus, there is ample opportunity—and need—to mainstream a GPN-focused perspective into AFS foresight work.

Individuals and organizations using foresight work to reimagine the AFS can support a multitrack strategy to incorporate both policy-led and innovation-led pathways through the following: (1) incorporating GPN into the design and implementation of their own programming, research, and practice; (2) supporting and advocating for the mainstreaming of GPN into the work of others; and (3) while acknowledging that global coordination may or may not be an achievable future outcome, supporting policymakers in recognizing the importance of GPN in the AFS by providing them with multisectoral and multilevel tools and analyses that systematically identify the net effects of AFS changes on GPN outcomes.

7.1 Gender

Among GPN, gender is the outcome least discussed across the foresight work. In studies that do consider gender, authors argue that prioritizing gender equality is essential for the successful transformation of the AFS (HLPE 2017; FOLU 2019; HLPE 2019; Quisumbing *et al.* 2019; Rawe *et al.* 2019). Gender norms and gendered inequalities often shape what roles are available to men and women within agricultural value chains. Assuming women are either only farmers or only consumers risks overlooking transformative opportunities

within the AFS to enable women to be fully engaged throughout the AFS (Quisumbing *et al.* 2019). Relatedly, few foresight studies consider how gender shapes the behaviors and barriers faced by men. Gender transformative changes to the AFS require partnering with not just women and girls but also men and boys, as well as changing norms and removing structural and institutional barriers (Quisumbing *et al.* 2019).

Few studies consider the structural and institutional barriers and social norms that influence individuals' abilities to adopt new technologies. Further, new technologies and new agricultural management techniques combined with pre-existing barriers may deepen gender and other inequalities (e.g. WEF 2018; Tittonell 2019; Skeer and Leme 2019; NAS 2019). Understanding unintended consequences is particularly important for supporting marginalized populations and addressing social exclusion within the AFS. For example, if innovations require additional labor requirements, gender-based time poverty may worsen or may contribute to gender-based productivity gaps (Simelton and Kawarazuka 2019). Similarly, aging populations may increase the time burden for (often female) caregivers and increase demand for convenience foods, potentially at the expense of health (Meenakshi and Webb 2019).

Future foresight work would benefit from taking an intersectional approach to understanding how gender interacts with other categories such as age, status, poverty, and ethnicity. Doing so will better identify the needs of and means to support the most marginalized (Huyer *et al.* 2019). These issues are relevant for foresight research on reducing poverty in the AFS as well.

7.2 Poverty

Several themes emerge around poverty. Poverty-related outcomes are presented in terms of food security (e.g. Palazzo *et al.* 2014), food prices (Hasegawa *et al.* 2018), or GDP, sometimes adjusted for inequality (Palazzo *et al.* 2014). Changes in food prices and GDP have differential effects based on the AFS role and poverty status of a given actor. Foresight studies do not consistently identify both consumers and producers. Few studies discuss the poverty impacts for other AFS actors (e.g. processors, transporters, and day laborers), although different sectors of the economy may experience different rates of growth: if GDP increases primarily in urban areas, urban consumers may benefit while rural producers are left behind. Further, few foresight studies advocating for the adoption of sustainable agricultural techniques discuss labor requirements (HLPE 2019). More attention to labor as an input in the AFS could help researchers understand the potential challenges to adoption and potential for poverty alleviation. Future foresight work would benefit from making explicit how various outcomes link to or interact with poverty. Further, few foresight studies recognize that consumers, producers, and other actors in the AFS can be impoverished and different policies may impact them differently.

7.3 Nutrition

Across studies, there is general agreement that overnutrition will rise under the Business as Usual case. Undernutrition may increase as well, particularly in South Asia and sub-Saharan Africa. Nutrition-focused foresight studies argue for a shift from production of staples (or staples and livestock) to greater access to and production of diverse diets. Several foresight studies chart pathways to expand the supply of affordable, healthy foods, ensure those foods reach consumers, and encourage consumers to eat them. These diets converge on low consumption of animal-based products and increased consumption of fruits, vegetables, and pulses. How to shift consumer demand toward more diverse diets remains an area of debate. Proposals include mixtures of policy nudges, changes to pricing, decreased waste, improved storage, expansion of nutrition-sensitive agriculture, and adoption of speed-breeding techniques. Changes will likely require systemwide interventions and policy guidance.

Shifts in consumer preferences are happening, but the direction and magnitude of these changes are currently ambiguous. There is substantial disagreement about whether more people will adopt Western diets or whether people will eat healthier, diverse diets. In some studies, production of calories (or calories and livestock) is the primary focus, with less attention to dietary quality and the role of horticultural products (e.g. Palazzo *et al.* 2014; NAS 2019). When studies focus on one aspect of the triple burden (e.g. expanding access to AI to increase yields), there is a risk that such technologies, if pursued in isolation, could adversely impact other forms of malnutrition (e.g. increased overnutrition due to the cheap and expanding availability of staples).

Other transformations in the AFS may hinder improvements in nutrition or support healthier outcomes. For example, increases in income may increase demand for unhealthy diets or enable impoverished individuals to afford healthier foods. Policies can support healthful consumer choices. Questions of consumer acceptance of biological-based crop production, biotechnology for plant-based meat alternatives, synthetic biology, gene editing, and the role(s) of livestock production remain (WEF 2018; HLPE 2019; FOLU 2019; Serraj *et al.* 2019). Finally, the impact of prices on nutritional outcomes is uncertain; prices interact with consumer behaviors, cultural norms, and choices (HLPE 2017).

7.4 Ways forward

The degree to which foresight studies consider GPN-related outcomes varies. Much of the foresight work that promotes socioeconomic changes to improve the AFS in a way that prioritizes GPN outcomes relies heavily on the assumption that global coordination of policies and regulations is possible. However, history has shown that efforts to coordinate globally have had mixed success; that is, relying on transformative global governance to lead AFS change may be a risky strategy. At the same time, other foresight work highlights the role of technology and improved management techniques in our future AFS. The paths for these innovations appear more certain and path dependent than the socioeconomic changes. Yet, innovation-led studies tend to pay less attention to the barriers to equitable adoption and to whether these innovations will support improved nutritional outcomes. The history of development has demonstrated the challenges of equitable implementation of new technological innovations. While not considered directly in most of these scenarios, this history suggests that there will be a range of emergent challenges in implementing and facilitating the adoption of new and potentially game-changing innovations in ways that do not exacerbate existing social and economic inequalities. Without GPN outcomes explicitly incorporated into foresight research, the value of this research to policymakers aiming to achieve the SDGs is diminished. Some of the uncertainty regarding GPN outcomes could be resolved through future foresight work that not only addresses this gap, but also prioritizes evaluating how and when to bundle or sequence interventions. Such research would help policymakers understand the effects of interventions on the entire AFS and what trade-offs may be required to transform the AFS into one that is sustainable, healthy, and just.

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Data availability

Publicly available reports were used in this study.

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