



Looking across diverse food system futures: Implications for climate change and the environment

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Abstract

Agriculture and food systems are in urgent need of transformation. Various foresight reports unpack food systems' challenges and propose diverse pathways of change towards sustainability. We interrogate the framings and proposed pathways of eleven selected reports from a food system perspective, with a focus on environmental and climate change implications. We synthesize key drivers of food systems and their impact on food system outcomes. We distil trends and strategies identified across the reports and their scenarios and discuss the diversity of 'sustainability pathways' and 'solution spaces'. There is general agreement that resource protection and adaptation balanced with significant greenhouse gas emission reductions are vital to food system transformation. There is less consensus on the choice of change options and how to address potential trade-offs. While new technologies or consumption changes are described, more attention needs to be paid to overcoming blind spots like implications for equity or changes in governance mechanisms.

Keywords: Food systems, Foresight synthesis, Climate change, Food security, Trade-offs, Pathways of change, Plurality, Food system equity

JEL codes: Q01 Sust Dev, Q5

1 Introduction

Agriculture and food systems are in urgent need of transformation. They currently do not provide the needed food and nutrition security outcomes while having far-reaching environmental and social impacts (ISPC 2018; Willett *et al.* 2019). Many interrelated challenges obscure how to transform the agri-food system towards environmental, economic, and social sustainability. Current food systems do not meet the food security and nutrition needs of all (ISPC 2018), despite significant increases in the production of food worldwide. Millions of people still go hungry and are malnourished—in fact, the number of people increased from 2015 to 2016 (FAO 2017). These problems will continue to worsen with the projected global population growth, increasing per capita consumption, changing diets, and associated growing impacts of environmental degradation. In addition, the current food system does not always produce the right food, as reflected by increases in diet-related health

issues (Clark, Hill and Tilman 2018; Clark *et al.* 2019; Lindgren *et al.* 2018), with non-communicable diseases coexisting with stunting and wasting in many countries. In addition to social and health outcomes, the agri-food system also has large implications for the environment. Agriculture currently uses half of the ice-free surface on the Earth (Ellis *et al.* 2010), and agricultural water withdrawals account for 70 per cent of all water withdrawals (FAO 2012). Agriculture negatively impacts the quality of soil resources and contributes significantly to biodiversity loss (Chaplin-Kramer *et al.* 2016; Pendrill and Persson 2017; Díaz *et al.* 2019).

Attempts to address the sustainability challenge of agri-food systems need to acknowledge that food systems are dynamic and complex. This complexity not only presents challenges, but also opens spaces for different ways of thinking about alternative sustainable pathways (Eakin *et al.* 2017; Béné *et al.* 2019). Taking a food system perspective that includes all activities from farm to fork and acknowledging the cross-scale interactions borne out of trade and other processes are important for understanding the potential role of the agri-food system transformation in contributing to global sustainability (Ingram and Zurek 2018; Kummu *et al.* 2020). The COVID-19 pandemic highlighted the shortcomings of neglecting the various interrelationships within food systems and helped to pinpoint the many vulnerabilities of the current structure due to, among others, just-in-time supply chains or labour shortages (Garnett *et al.* 2020).

There are different ways of perceiving the food system, which often leads to seeing different root causes to problems and solutions to address them (Béné *et al.* 2019). Deeper understanding of these different food system framings will equip actors to better govern sustainability transitions (Loorbach *et al.* 2017) and deal with the uncertainty embedded in future pathways (Stirling 2011). Foresight processes, such as trend analysis or scenario planning, can be helpful here as they systematically explore the factors and processes that drive transformation and the uncertainty surrounding the potential effects of innovation options on the whole system. They also offer mechanisms to explore alternative future trajectories that may not currently be on the radar of policymakers by exploring multiple pathways in which the future may unfold, therefore directing funding and programmes towards these alternatives.

This paper assesses eleven recent forward-looking food system reports to synthesize the main drivers of the food system change they identify and interrogate their proposed pathways of change, focusing particularly on the implications for climate change and the environment. The paper builds on a report commissioned by the Independent Science for Development Council of the CGIAR (Zurek *et al.* 2020) to synthesize the findings of these eleven reports and give recommendations on the implications of the identified food system challenges and proposed pathways on the work and the ongoing reform process of the CGIAR. Here, we maintain that food systems rely on natural resources as key inputs, while the status of natural resources relies on the way food systems are managed.

We use a food system lens, which recognizes drivers (social, economic, and environmental), actors and activities (i.e. the whole supply chain), and outcomes (e.g. food and nutrition security) (Ingram and Zurek 2018; Ericksen 2008a), to uncover similarities, differences, and blind spots across these reports. We also explore the drivers as well as the possible outcomes of food systems by looking at how the pathways described in a subset of reports that developed scenarios contribute to these outcomes. We conclude by outlining gaps in the reviewed forward-looking food system reports and present a set of opportunities that different actors, such as the CGIAR and other practitioners, policymakers, or donors, should consider to incentivize and support the needed transformation of food systems towards environmental, social, and economic sustainability.

2 Methodology

2.1 A food systems approach

We build on a food systems approach proposed in Ingram and Zurek (2018). The food system is made up of several food system activities, including primary production,

processing, retailing, and consuming, along with storage and waste disposal (Ericksen 2008a; Ingram and Zurek 2018) undertaken by different actors. Food systems also involve multiple interacting value chains (Kummu *et al.* 2020) and are driven by the wider context of human and natural systems and by multiple interactions and feedback loops (Zurek *et al.* 2018). The food system produces multiple outcomes and its ability to do so is influenced by multiple environmental, economic, and social drivers. In this paper, we focus only on the drivers and outcomes of the food system.

Food systems approaches are increasingly used to assess the direction of change dynamics towards sustainable food systems. They can also be used to explore the system's functioning with respect to its outcomes, its drivers, and impacts upon the actors that make up the system (Zurek *et al.* 2018). Systems are 'designed' with certain outcomes in mind, so are food systems (Meadows 2008). The main outcomes of the food system can be categorized into three areas: food and nutrition security, economic and social well-being, and environmental sustainability (Woodhill, 2019). The approach can also be used to assess whether a particular food system design can deliver on its main outcomes. Moreover, a system lens is also employed to explore possible options for change, as well as uncovering how drivers of change variedly impact upon actors, resulting in winners and losers (Eakin and Luers 2006; Ericksen 2008b).

Drivers of food system change include demographic developments, wealth distribution, consumption preferences, technological developments, market arrangements, politics, and climate and environmental factors (Ingram 2011). A 'driver of change' is 'any natural or human-induced factor that directly or indirectly causes a change in a system' (MA 2003). Drivers influence the functioning of the food system and can do so in varied ways. A single driver can directly influence the system, but this can also happen after interaction with one other or more drivers. In fact, different drivers can be interlinked: for example, agricultural inputs pollute water ecosystems and the polluted water affects water availability for agriculture. In most cases of interlinked drivers, a direct driver that affects the food system does so through indirect influence of societal values and choices (IPBES 2019). For instance, while climate change and environmental change have direct effects on the food system, socioeconomic dynamics (such as diet changes, economic models, the growing preference for convenience and ready-made meals, demography, urbanization, and migration) are some of the underlying causes of these direct drivers. Moreover, drivers and outcomes can be interlinked and mutually reinforcing. Drivers are one of the main entry points to manage and steer food system change, as they can be manipulated to move the system onto a different, desired trajectory (Meadows 2008). However, drivers also paint a picture of where in the system the main influences might come from. For example, the fall of government funding for agriculture around the world opened up a window for the private sector to step in, although this resulted in market power accumulation and other consequences (Clapp 2016). Another entry point for change in food systems is to reconfigure the relationship between the system elements, such as the relation between food system actors and their activities, making them more resilient towards sudden driver impacts. To explore the impact of such options for change, we take a forward-looking perspective that we describe in some detail in the next section.

2.2 Foresight—a forward-looking perspective

Food systems present high degrees of uncertainty and may evolve in ways that cannot be entirely predicted and controlled (Vervoort and Gupta 2018). This is due to the interplay of human and natural systems that make up food systems, which makes them complex adaptive systems (Levin *et al.* 2013). In many decision-making contexts, anticipatory planning is increasingly used to explore how driving forces might differently shape the future (Quay 2010; Boyd *et al.* 2015; Vervoort and Gupta 2018). A number of tools exist to explore the

future and aid in decision making (Henrichs *et al.* 2010). These include trend analysis and trend extrapolation, forecasting (e.g. Armstrong 2001), cross-impact analysis (e.g. Gordon and Hayward 1968), future workshops (e.g. Jungk and Müllert 1987), Delphi-type expert-based estimates (e.g. Helmer 1983), role playing, gaming, and simulation (Vervoort *et al.* 2010), and future state visioning (e.g. Stewart 1993), as well as the development of future histories, science-fiction writing (Merrie *et al.* 2018), and also wild speculation.

Most commonly used are scenario approaches, in which scenarios can be defined as ‘plausible and often simplified descriptions of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces and relationships’ (MA 2005). They are useful not only for developing robust strategies to cope with the different ways the future might play out, but also for entering into tailored strategic conversations with decision-makers about difficult choices and trade-off decisions (MA 2005; IPBES 2019). An important function of scenario analysis is to provide an approach to reflect on and think through the possible implications of alternative decisions in a structured manner (Hebinck *et al.* 2018). A scenario exercise offers a platform that allows individuals, companies, organizations, or countries to reflect on how changes in their respective context may affect their decisions. In doing so, scenarios explore a range of plausible future changes, while considering future uncertainties. There are several scenario approaches, which each have different objectives. ‘Exploratory scenarios’ start from the present and explore the potential impacts of various drivers, trends, and interactions from now into the future (Henrichs *et al.* 2010). However, ‘normative scenarios’ or backcasting exercises start from a particular vision of the future and work their way backwards to identify pathways for reaching this future (Henrichs *et al.* 2010). Applying a forward-looking perspective entails considering future developments of the system, considering uncertainties and dynamic system elements, often leading to multiple plausible outcomes.

2.3 Operationalization: looking across food system futures

Using the food system and foresight perspectives, we interrogate eleven reports that set out food system futures. The selection of the reports was guided by a consultation process for the Independent Science and Partnership Council (ISPC), an advisory body of the CGIAR, which specifically outlined reports that connect to global food system dynamics. Although the reports analysed in this paper do not represent the full scale of foresight studies on food, we use them for illustrative purposes and our intention is not to cover the full scope of foresight studies. We assess their proposed pathways of change and how they compare to each other with respect to sustainability transitions. Table 1 shows the selection of reports that have been taken into consideration in this paper. The reports vary substantially in their specific foci and the parts of the food system they address, and the foresight components used in their analyses.

To operationalize our comparison of pathways of change across the diverse reports, we first review the key drivers of food system change (i.e. governance, markets, technology, and societal dynamics) and analyse how the reports link driver dynamics to food system outcomes (both in quantified terms and conceptually). In doing so, we wanted to paint a picture of the diverse system understandings across the reports. Second, we assessed options for change towards sustainability proposed by the reports. Each of the reports proposes certain solutions based on the food system they envision and their perspectives on how change can best be implemented. Third, to analyse the different pathways of change proposed across the reports, we interrogated the reports’ scenario-based pathways of change and their hypothesized future impacts. This overview allows us to reflect on their claimed future sustainability impacts and relation to food system transitions, while distilling a number of food system trends and challenges. From this analysis, a number of findings emerge for

Table 1. Overview of the forward-looking documents on food system change considered.

Report title	Food system focus	Foresight component
'FOLU' (FOLU 2019)	Food systems	Scenario modelling of impact on a number of key drivers and outcomes—baseline and a proposed change scenario
'GAIN' (Hansen <i>et al.</i> 2019)	Innovations for nutrition security	Twelve innovations to reduce the price of nutritious food, address food safety issues, and increase shelf life, in low- and middle-income country settings
'GKI' (GKI 2017)	Supply chain innovations	Short-term achievable (5–10 years) innovations that address current challenges
'HLPE' (HLPE, 2020)	Food security and nutrition	Building a narrative and potential policy pathway towards food security and nutrition
'ISPC' (ISPC 2018)	Food system drivers	Identifying drivers that are considered key to future developments
'NAP' (National Academies of Sciences, Engineering and Medicine 2019)	Agriculture (and food/nutrition)	Assess the role of several scientific breakthroughs in advancing food and agriculture
'RethinkX' (Tubb and Seba 2019)	Alternative protein production	Technology trajectory analysis
'WEF' (WEF 2017)	Food systems	Four global food system scenarios comparing high and low connectivity in the world, as well as resource-intensive and resource-efficient pathways
	Plant breeding/biotech	Expert report
'WIPO' (Graff and Hamdan-Livramento 2019)	Food systems	Scenario modelling of impact on a number of key drivers and outcomes—baseline and three proposed change scenarios
'WRI' (WRI 2019)	Food production and food consumption	Scenario modelling of impact on key drivers related to environment and diets—baseline and all possible combinations between drivers
'EAT' (Willett <i>et al.</i> 2019)		

policymakers, practitioners, and donors to consider for stirring and incentivizing food system change.

3 Results

Here, we highlight some of the findings on similarities and differences for food system drivers and their potential impacts on food systems in the future. We also highlight the pathways identified in the reports to respond to these drivers (Table 2). The full comparison from a foresight and food system perspective is presented in Tables A1–A7 in Appendix A and can be found in the full report (Zurek *et al.* 2020). Each of the studies provides different analyses of food system challenges and suggests opportunities embedded in drivers that offer options for change. What these proposed options for change do not reveal is the wider system context within which they will play out. Only studies that provide a set of scenarios to describe plausible future conditions address this systemic context in more detail.

3.1 Key food system drivers and solution spaces

Food system change is driven by a wide range of different factors that include environmental, social, economic, technological, demographic, and political drivers. A key example is the impact drivers of climate change and environmental issues have on the system's ability to deliver food system outcomes, while simultaneously these outcomes in turn also fuel climate change and environmental issues (Table 2). Exploring the interaction patterns of drivers in a systematic way is crucial to uncovering the drivers that are considered paramount, as well as their associated impacts. Below we report the set of drivers we identified as key to future food systems. In addition to climate change and environmental change, we also identified other drivers that are influential and crucial to consider.

3.1.1 Reflecting on proposed solution spaces

Depending on the specific food system perspective, entry points for addressing food system challenges (i.e. trends and drivers) differ by scales and levels, and have varied change mechanisms. Social change, such as dietary changes, is multidimensional and can either exacerbate environmental and climate change (through overconsumption, wastage, and pollution) or improve towards sustainability (through less red meat consumption, shortening supply chains, and using nature-friendly agriculture). Overall, the reports either propose a change in the direction and intensity of the described trends or propose to change the interactions among drivers as a way to steer food systems in the desired direction. Moreover, the solutions can differ considerably in terms of their 'direction' of change. While the direction of change can be compared through a future perspective, understanding the mechanisms of change can be done by assessing what reports consider a 'pathway of change' (see tables for each driver in Appendix A for a full overview). Across existing food system future research, we see both comprehensive and integrated approaches that address a wide range of drivers, as well as pathways that focus on one or a few disruptive innovations.

3.1.1.1 Disruptive innovations for sustainability

Pathways of change that employ primarily disruptive innovation as a way to address food system challenges are mostly technology oriented. These technologies include innovations that attempt to redirect sustainability of food production, processing, and retail. Examples in the reports include the introduction of precision fermentation as a completely new way to produce proteins for human consumption or the use of Big Data and artificial intelligence (AI) for precision agriculture. What these innovations have in common is that they aim to redirect the direction or the intensity of a driver that is considered problematic in the short term.

Table 2. Food system drivers and their trends across the analysed reports.

Food system drivers	Current driver trends	What the reports say
Climate change	Change in climate variables Rise in extreme events	Changes in climate variables (e.g. changes in mean temperatures) will likely affect food systems (ISPC 2018; FOLU 2019; Tubb and Seba 2019; WRI 2019). These changes are foreseen to have large-scale effects on all parts of the food system and across developed and developing countries alike (ISPC 2018). For example, temperature changes will affect crop yields in most parts of the Global South negatively, while some areas in the Northern Hemisphere might gain in yields (WRI 2019). Weather-related shocks (e.g. floods and droughts) are expected to increase and can have catastrophic impacts on the increasingly vulnerable global food system. These extreme events are expected to make it difficult to achieve much of the global and national policy targets, such as the SDGs (ISPC 2018), may reduce land productivity and yields (WRI 2019), and increase erosion (FOLU 2019). Reports also discuss the rising GHG emission profile of the food sector and the associated need for mitigation actions (GKI 2017; WEF 2017; ISPC 2018; FOLU 2019; RethinkX 2019; WRI 2019). Rise in GHG emissions and the subsequent exacerbated climate change will also affect other elements of the food system. For example, a consistent and extended decline in sea ice would result in more frequent disruption of major trading ports due to sea-level rise (ISPC 2018).
Environmental issues	Water scarcity and pollution Nutrient scarcity	There is widespread concern for water pollution from food production into water courses (ISPC 2018; FOLU 2019; NAP 2019; HLPE 2020). This pollution in turn affects water availability for agriculture and water scarcity is expected to be a continuing problem—with half of the world's population expected to live in water-stressed areas by 2050 (FOLU 2019). By some estimates, the world has exceeded the planetary boundary for nitrogen (Steffen <i>et al.</i> 2015). The ISPC estimates that nutrient demand will double by 2050, and FOLU asserts that nitrogen-use efficiency varies widely by region and crop. Phosphorus scarcity could prevent agricultural intensification by limiting intensive agriculture (Tina-Simone and Cordell 2012) and impact on the ability to close yield gaps (Mueller <i>et al.</i> 2012). On the other hand, increasing application of nutrients pollutes waterways, affecting the agri-food sector itself.

(Continued)

Table 2. (Continued)

Food system drivers	Current driver trends	What the reports say
Land use competition	<p>Agriculture remains the dominant land use globally (Foley et al. 2011) and it is expected to increase in the future. However, reports foresee the competition for land between food production and other land uses intensifying as other uses such as biofuels and non-food crops become prominent (ISPC 2018; FOLU 2019; HILPE 2020). Production of non-food crops for biofuels was initially linked to solutions aiming to address climate change by providing a renewable source of energy.</p>	
Land grabbing	<p>Large-scale land acquisition, also known as ‘land grabbing’, is seen to be increasing in recent years (WRI 2019). What is troubling, however, is that the acquisitions for agricultural land are not necessarily used for production but are used by large investors for speculation (Agrawal, Brown and Sullivan 2019).</p>	
Biodiversity loss	<p>Biodiversity loss will continue in the future. FOLU reports that even in the best-case scenario, biodiversity intactness is expected to decrease (FOLU 2019). This is further exacerbated by expected expansion in agricultural production in the future. The recent global assessment by the Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services confirms that over the last 40 years, biodiversity has declined significantly in the world—and will likely continue to decline unless drastic measures are taken (IPBES 2019).</p>	
Soil degradation	<p>Soil degradation has a complex relationship with the agri-food system. Degraded soils contribute to declining yields, which in turn lead to overapplication of fertilizers, which further degrade the land and water quality. Soil degradation is expected to continue as demand from countries in one part of the world results in soil health decline, biodiversity loss, and other environmental degradation in other parts of the world through long supply chains (Wiling et al. 2017; Lenzen et al. 2012).</p>	
Overfishing and aquaculture growth	<p>There is widespread evidence of global overfishing (Watson et al. 2013), which is expected to continue into the future. Wild caught fisheries are no longer sufficient to meet demand (GKI 2017; FOLU 2019; WRI 2019), and aquaculture has now surpassed wild caught fisheries in total quantity (WRI 2019). Aquaculture development as a driver has implications for land use (through increasing use of land grown feed for fish, overfishing for feed, and water demand for irrigation of land-based fish feed) (NAP 2019).</p>	

(Continued)

Table 2. (*Continued*)

Food system drivers	Current driver trends	What the reports say
Social change		<p>Social drivers are in fact the indirect drivers of most of the climatic and environmental drivers (IPBES 2019). Dietary changes, for example, are expected to fuel much of the expected land use change, GHG emissions, and biodiversity loss. This changing culture of food has seen increases in non-communicable diseases (Clark <i>et al.</i> 2019) and increasing preference for ready-to-eat, processed meals. Inequality and food insecurity (ISPC 2018; FOLU 2019; WRI 2019) are also increasing globally, despite gains in agricultural productivity and increases in national incomes. Market innovation, fair food commerce, and green technologies are expected to play an increasing role in the future and are seen to be important to determine the ability of the food system to transform to a sustainable pathway.</p>
Market dynamics		
Governance dynamics		<p>The roles of diverse partners are highlighted: government and their role to regulate through taxes and policy incentives, addressing land tenure issues, and protecting natural landscapes (FOLU 2019; WRI 2019); and international organizations for investing in infrastructure and R&D (WRI 2019; WEF 2017; FOLU 2019). There is acknowledgement that the private sector, public sector, international organizations, non-profits, and donor and investment funds need to make a concerted effort to scale innovative technologies.</p>
Technological developments		<p>Across all reports, technology is expected to play a significant role in driving the system, from advances in breeding techniques for crop yield improvements and precision breeding (WEF 2017; WRI 2019), convergences of Big Data and biotechnology (WEF 2017), improvement in land management techniques (GKI 2017; FOLU 2019; WRI 2019) to targeted innovations for small-scale procedures and processors (GKI 2017) and renewable energy, which should be scalable and accessible (GKI 2017; WEF 2017; FOLU 2019; WRI 2019).</p>

3.1.1.2 Transformative change pathways

Other perspectives to furthering change towards sustainability feature more comprehensive and integrated pathways of change. Notable in these pathways is that they generally offer options that address multiple drivers in order to steer food systems in a more desired direction. These pathways fully acknowledge that food systems are complex and adaptive systems and therewith require action on multiple levels and scales, as single actions might not lead to the desired impact. For this reason, such transformative pathways are often accompanied by a vision for a sustainable food system, giving a sense of direction. Such integrated pathways of change build on comprehensive food system understandings and generally attempt to redirect interaction patterns of drivers, as well as individual driver trends. A major example of this is the identification of a trade-off that features food demand, land use, and greenhouse gas (GHG) mitigation needs as the paramount obstacle to achieving more sustainable outcomes (WRI, FOLU). Addressing this requires a ‘menu of change’ aimed at addressing multiple mechanisms of change. This includes technological innovations aimed at increasing crop yield, reducing GHG emission from livestock, and more effective supply chains, which address the direct drivers of food systems and the outcomes they deliver, as well as addressing indirect drivers of food systems, such as consumption behaviour, fair commerce practices, or land tenure, which aim at changing the interaction pattern they have with the earlier mentioned direct drivers. Here, addressing direct drivers only is considered useful only for the relief of symptoms. Addressing the interaction patterns focuses more on the root causes of the challenges. These pathways are complex and span the entire food system, addressing all broader driver categories via multiple actions. Revealing their impacts of change can only be made visible through comparison with a ‘business as usual’ (BAU) pathway, which is done via scenario analysis. Such transformative change pathways attempt to overcome the adaptive and complex nature of food systems and all require extensive action to be taken by all food system actors.

3.2 Future food system outcomes in scenario-based reports

This synthesis compares a subset of four reports (FOLU, WRI, WEF, and EAT), which have fully developed scenarios (based on known or hypothesized, new drivers’ interactions) to assess the impacts of their proposed pathways of change. A short write-up of the narratives underlying each scenario can be found in Appendix A and the full report (Zurek et al. 2020) and more details can be found in the reports themselves. We compare the different scenario-based analyses to evaluate their findings on the ability of future food systems to deliver on three key food system outcomes: *food and nutrition security*, *environmental sustainability*, and *economic and social well-being*. WRI, FOLU, and EAT scenarios use a baseline and show outcomes based on the BAU approach. They each offer approaches for dealing with identified BAU challenges and steering food system dynamics towards delivering on all food system outcomes. The WEF scenarios do not develop a baseline scenario and instead use exploratory scenarios to show how four different combinations of drivers might shape the future, affecting food systems and their ability to deliver outcomes.

3.2.1 Environmental sustainability and climate change

Two key areas of climate change concern for the food system are mentioned across all the reports—namely (1) food system adaptation to changes in biophysical climate variables and extreme events, and (2) reducing GHG emission profiles of food systems substantially via various supply- and demand-side measures.

However, with respect to adapting to climate change, WRI states that the evidence from crop models suggests significant capacity to adapt. However, there is high uncertainty about the extent to which adaptation can offset the adverse effects of climate change. In addition, some reports raise the question of where agriculture should take place and to what extent

Table 3. CO₂ emissions from food systems in Gt as mentioned in the reports.

Report	Baseline 2010	Baseline 2050	Pathways of change 2050			Paris target 2030
			Scenario 1	Scenario 2	Scenario 3	
WRI		15.0	9.1	5.8	4.6/0.0	
FOLU	12.0	13.0	0.0	–	–	4.0
EAT		9.8	4.0	–	–	

more predictable weather will result in stable food supplies. An important connection is made between adaptation and biodiversity conservation in the FOLU and WRI reports as the need for more agrobiodiversity is seen as a strategy to promote more climate-adaptive agriculture.

All reports give much attention to total levels of GHG emissions and specifically to the food system's contribution of GHG emissions, but assumptions about emission reduction targets in line with the Paris Agreement differ. For example, although 4 Gt CO₂ is seen as the limit for food system emissions up to 2030 in some reports, all emphasize the need for net-zero-emission food systems by 2050. Table 3 shows the different assumptions about the trajectory of baseline trends in three reports. These differences therefore also influence the pathways-of-change scenario chosen by various reports. To make sense of what this means for the future of food systems, we must highlight some of the differences between the reports. The scenario analysis in the three reports starts with different assumptions that are important to understand when comparing their results on climate change mitigation actions. First, EAT does not question food demand and purposely looks at how dietary health and planetary impacts can be matched: it does not consider a situation where a portion of the global population does not receive adequate nutrients. FOLU's *better futures* scenario, on the other hand, assumes in their change scenario that the global population shifts to the *planetary health diet* as outlined in the EAT diet and that the SDG2 target to end hunger is met in 2030. Additionally, the *better futures* scenario assumes that global temperatures in 2050 will stay within 1.5 °C, as prescribed by the Paris target, while reforestation is a key mechanism to reduce food system emissions to net zero. As such, these scenarios are less informative on how changes in land use and agricultural methods will influence GHG emissions and can be a lever for change in meeting emission targets.

In contrast, the WRI report does not assume there will be enough food in 2050 and specifically sets out to explore how food demand can be met while attempting to address the other challenges. In doing so, it sets out various levels of ambition in implementing action. It shows that neither a *coordinated effort* alone nor a high *ambition* pathway regarding both governance and technology is sufficient to bring down emissions to a desired level. This result can be accounted for by the lack of progress made in food production and yield increases, leading to a need for land expansion to meet food demand. Only when combining these efforts with *breakthrough technologies* can GHG emissions be brought down to a level that almost meets the Paris Agreement. Here, a sharp increase in yields and considerable reduction in food loss and waste result in the freeing up of land for reforestation. The report further outlines an addition to the scenario that includes ecological restoration of much of the freed-up land, resulting in a net-zero-emission scenario.

With respect to land resources, the baseline scenarios in the reports show that extra measures are needed in order to make sustainable use of water and soil, as the availability of freshwater for food systems and water pollution continues to be a serious issue in the future. However, the reports see this as being connected to soil management and nutrient cycling. For example, in WRI's baseline scenario the authors assume improvements are made in terms of nutrient cycling and in turn soil quality even in the BAU scenario. However, the

potential positive effects these improvements might have on the water system are cancelled out by the need to increase food production and expand agricultural lands, leaving less fresh-water available for food systems. The other scenarios incorporate a variety of soil and water management practices to improve the status of land resources. FOLU features regenerative agricultural practices, which include a high level of nutrient cycling, low levels of irrigation, and no use of pesticides to produce food. FOLU also assumes a more careful consideration of spatial planning with regard to crops and livestock: that is, making sure crops are not grown in places where they require high maintenance. Similar strategies are outlined in the WRI report, combined with technological advances that allow for a considerable increase in yields. Coupled with the varied levels of food demand and land use pressure in WRI's scenarios, these strategies provide useful insights into soil and water management from a system perspective.

The amount of land available for agriculture is a main concern in the future, especially because this is a variable that is static. The reports unanimously underline the intimate connection between agricultural land use and biodiversity and GHG mitigation. Clearing natural landscapes for agricultural production leads to a loss of carbon sinks and wild biodiversity in flora and fauna. Land use fragmentation is considered a further pressure on biodiversity, as it would reduce natural landscapes to small patches, especially threatening a biodiverse fauna. The scenario-based food system outcome assessment shows this relation clearly as well as negative impacts across the baseline scenarios. All show a food demand-driven expansion of agricultural land, resulting in further fragmentation of land and a decrease in biodiversity. All change scenarios in the report emphasize that a decrease in agricultural land use opens space for wild biodiversity. FOLU and WRI specifically highlight the need for more agrobiodiversity as a strategy to promote more climate-adaptive agriculture.

A third essential outcome that needs to be secured for environmental sustainability relates to marine resources. Increasingly, marine resources are emphasized as a sustainable option in the protein dilemma that results from growing food demand in the future. Aquaculture is considered a biodiverse-friendly option for increasing fish protein. However, the scenarios also emphasize a dual relation between marine harvesting of fish and aquaculture. While an increase in aquaculture could relieve marine stocks, some scenarios also emphasize that current systems rely on wild fish and land-based feed production as inputs in fish feed for aquaculture, putting pressure on wild fish stocks and taking up valuable space. The scenarios propose putting protective measures in place. FOLU considers sustainably produced fish to be a crucial part of the protein puzzle, while WRI sees the potential for sustainable fish protein to contribute to overall protein demand as limited. Both highlight the need for innovation in the aquaculture sector and for policy reform to better manage wild fish stocks.

3.2.2 Other food system outcomes: food and nutrition security and economic and social well-being

The analysed scenario reports contain, of course, also a wealth of material on possible future food and nutrition security outcomes under different assumptions and on economic and social well-being. Here, we just provide a few highlights of the findings; more details can be found in the full report (Zurek *et al.* 2020).

3.2.2.1 Food and nutrition security outcomes across the scenarios

With respect to food and nutrition security outcomes, we analysed the scenario reports' findings on food availability, utilization, accessibility, and stability. Notable across the scenario reports is the emphasis that these put on increasing both crop and livestock yields to meet the continually growing demand for food in the future. All the intervention scenarios also emphasize the need to reduce food loss and waste as a crucial element in meeting food demand. There is also unanimous emphasis on the need to increase total food production. WRI's *breakthrough technologies* scenario shows how a significant reduction in food

loss and an increase in yields could reduce the urgency of increasing total food production, freeing up space for other land uses.

With respect to food utilization, nutrition and health links are a major concern for the future as current global trends project that a large proportion of the global population will suffer from severe nutrient deficiencies and another large proportion will suffer from overweight and obesity. Each of the scenarios highlights the need to push nutritional patterns in more healthy directions. In WRI, the emphasis is predominantly on a nutrition-secure population, arguing that meeting total food demand will be one of the major challenges in the future. The focus in FOLU and EAT is more on curbing growing obesity, based on the assumption that total food demand will be met. This approach allows these scenarios to focus more on the actual nutrition profile. It is therefore difficult to compare the conclusions we can draw from these two different perspectives and pathways, apart from emphasizing that nutritional status will remain a major vulnerability on a global level.

With respect to assessing food accessibility across the scenarios, we looked at food affordability, food distribution at various levels, and regional self-sufficiency. Little is said about actual food affordability: while FOLU stresses the need for fairer prices, WRI emphasizes the need for more research into the role of food prices in both sustainability of diets and poverty. There is ongoing debate about the need for accessibility versus availability: some emphasize that sufficient food is currently produced and that the major problem is inequitable distribution of food. Interestingly, all scenarios go beyond this debate and argue that the expected population growth urgently requires more food that is better accessible. They also all emphasize that to improve food distribution, there needs to be better global coordination among actors to share knowledge and technologies beyond the currently existing relationship of dependency between Global South and Global North countries.

Food system stability, another component of food security, is not comprehensively assessed in any of the scenarios, though they acknowledge that a stable, conflict-free food system is imperative for achieving food security.

3.2.2.2 *Economic and social well-being*

The third key outcome of food systems is described as economic and social well-being. We assess this outcome by focusing on livelihood opportunities and equity considerations. The reports echo the importance of food systems as a source for livelihood opportunities for a large part of the global population and emphasize the importance of maintaining these so that food systems can be socially sustainable. Livelihood opportunities can be assessed at various levels, and therefore we explore the following variables: the number of jobs food systems offer, the percentage of GDP that is made up by food systems (to assess the importance of food system activities to national economies), and finally, the income that farmers receive. We use the latter variable to assess whether food production remains a viable livelihood option, as food producers today are often the actors in the food system that get 'squeezed' and carry most of the risk.

Across the reports, few make concrete conclusions about the impacts of food system changes on these variables. However, the importance of this topic is signalled by the urgent calls for accessible and scalable innovations. The only report that makes a judgement on livelihood opportunities is FOLU, which proposes a shift to more localized and regenerative agricultural systems. Here, FOLU argues that such systems could embed more livelihood opportunities as well as ample business opportunities in the production and innovation process of sustainable foods. WRI emphasizes the number of people who rely on agriculture for their livelihood and the necessity to carefully weigh options and see how they impact people's lives.

The second crucial element in assessing economic and social well-being outcomes consists of equity considerations. Here, we consider various levels of impact, ranging from the individual to the country level. While each report has something to say about equity and the

need to act, few set out what actual impact such actions might have. Both FOLU and WRI emphasize the need for education for women and girls and access to reproductive health care, but neither forecasts how gender relations might change in the future. FOLU assumes that through these added measures, combined with more regionalized systems, gender equity will increase. FOLU expects that these localized systems will allow for more self-sufficiency, resulting in less dependency on global trade processes and a better balanced relationship between Global South and Global North countries. Both FOLU and WRI highlight the need to reform land tenure, which currently favours larger and more powerful actors. Both see a crucial role for local actors in conservation and food production.

4 Trends and strategies to consider in pathways towards sustainability

All the analysed foresight reports agree that climate change and environmental issues will continue to be prominent drivers of food systems in the future and will have to be addressed in any pathway towards sustainability. This section synthesizes a number of key findings for food system transformation that should guide the design of pathways of change regardless of underlying assumptions about how the transformation process could work.

4.1 Continued urgent need for action on climate change and environmental issues

Across the analysed foresight reports, four main findings on climate change and the environment emerged: (1) the continuing need for food system adaptation to climate change; (2) the need to lower food systems' GHG emission profiles; (3) balancing climate change adaptation measures with the need for reducing the environmental footprint; and (4) the need for reducing the continuing pressures on agricultural land management and agricultural expansion.

Besides stressing that climate change impacts will continue or even worsen in the future, all reports expressed the need for adaptation efforts across the entire food system and all regions. This is analysed especially for the agricultural sector, but other parts of the food system, such as transport, storage, or retail systems, will also have to adapt. High uncertainty nevertheless remains about the extent to which adaptation can offset all adverse effects of climate change and what the potential impacts of insufficient adaptation might be (WRI).

The foresight reports highlight the requirement to change the GHG emission profiles of current food systems, in both developed and developing countries, if we are to reach the goals of the Paris Agreement. The scenario-based assessments show that efforts to reduce GHG emissions from food systems require hard decisions concerning land use for food production versus renewable energy production, as well as the need to change food demand/consumption patterns. While all reports stress the demand for carbon sinks through reforestation and peatland restoration, they also acknowledge the need for a growing amount of land to meet food demand, especially if climate change adaptation measures cannot cope quickly enough with future climate impacts. One of the most crucial levers for meeting both climate and food targets is seen as technologies that can considerably improve yields and reduce food waste and loss, thereby reducing the need for agricultural land expansion and associated emissions.

Balancing the need for investments in adaptation measures across the entire food system with the needed investments in GHG emission reduction actions will be one of the tough choices for many countries in the future, particularly in a developing country context. Balancing both goals requires careful navigation of priorities and new technologies and incentive structures.

Another finding across all reports is that the expected growth in food demand will continue to put pressure on land resources in the future, resulting in various agricultural land expansion scenarios. These will have wider implications for global loss of biodiversity and the degradation of natural resources such as water and soil. The rapid expansion of agricultural land into forest areas to meet growing food demands is cited as a major cause as well as poor agricultural land management that further exacerbates soil and water quality degradation. Here, yield increases, together with improved land and water management practices, are seen as a crucial lever to reduce these pressures, with more efficient food production expected to require less land expansion. While roughly pointing to the same direction, there are two main angles to address the environmental challenges. What these two perspectives have in common is that they attempt to create alternative and more sustainable scenarios that meet a growing demand for food by reducing food waste and losses and increasing yields through technological innovation. While also central to both is the need to increase carbon sinks, they differ in foci: either transitioning to agricultural systems that function as carbon sinks or through massive reforestation and peatland restoration efforts. The first puts emphasis on the prioritization of mitigation over adaptation efforts, also for countries that have not been the heavy polluters so far. This primarily sets out an agricultural transition pathway to net-zero-emission farming techniques, which is argued to be made possible by scenarios that include regenerative agriculture. The second angle specifically sees challenges connected via a major trade-off around land use management, growing food demands, and food system GHG emissions. This entails making hard decisions when it comes to global land use planning and where best to locate forest restoration to increase carbon sinks, but will also rely on the development of breakthrough technologies across the food system. Scenarios indicate that geographical differentiation for efficient allocation of spaces might be difficult, as carbon sinks might unfairly lean towards developing-country context, while spaces for production might move further north.

4.2 Addressing other future food system challenges

While addressing climate change and environmental issues needs to be included in any pathway of food system change, a variety of complementary ingredients are proposed to make up a menu of change, ranging from technological developments to governance options. Here, we highlight three additional key considerations: (1) technological innovations for sustainability; (2) the need for healthy and sustainable diets; and (3) the need for just transitions.

Central to many approaches of food system change are technologies: both existing technologies and anticipated, new technologies that still need to be developed. The need for innovation processes that support more sustainable activities across the food system is accentuated across the foresight reports, from the agricultural system (e.g. precision breeding and regenerative agriculture) to changes in consumer behaviour (e.g. nudging via changed food environments and labelling). However, for technology to have the wanted impact, it needs both coordination of innovation across the food system and to be widely accessible. Coordination of innovations is vital to enable transformative change, as single innovations could have unintended impacts on other parts of the food system, especially when concerning disruptive innovations, which surprisingly have only been considered as potential solutions in a relatively limited scope (i.e. those that they seek to replace). Moreover, certain innovations are considered possible game changers for sustainability when made widely accessible, accentuating the importance of thinking of both political and market dynamics that govern innovation systems. This is also the issue for research funding and how it shapes the types of technologies available to various actors. Overall, the foresight reports are less clear on the governance arrangements that are needed to achieve such coordinated technology-driven transformation.

Dietary change is seen as a paramount lever towards sustainability, as current trends indicate further exacerbation of the triple burden of malnutrition. Healthier and more balanced diets are those that go beyond meeting caloric needs only and provide good nutrition. This requires a shift towards diets that include more fruits, vegetables, and nuts. From an environmental impact perspective, a move away from meat and towards inclusion of alternative sources of protein (i.e. plant-based, insect-based, precision fermentation, etc.) is required. While all pathways are aimed to meet the two objectives of good nutrition and environmental sustainability at a global level, they do so by putting emphasis on different aspects. For example, some pathways are aimed at identifying the dietary change patterns that are ecologically most appropriate, generally assuming food security can be met (FOLU 2019; Willett et al. 2019), while others consider the ability to meet food security as part of the dietary change challenge and assess the ecological potential of possible dietary change within the boundaries of food secure scenarios (WRI 2019). Each of these pathways includes strong emphasis on alternative sources of protein, bridging to the earlier mentioned innovation processes. Although much progress is made regarding plant-based protein sources that aim to mimic meat, reports point to the necessity to explore other sources too, such as mariculture of bivalves (including oysters, clams, and molluscs), insects, or algae. In recent years, aquaculture was considered the new frontier regarding sustainable protein sources; nowadays, it is also considered a threat to land use, as supplements for feed are often grown on land, competing with food production. None of the scenarios work though that take a full system perspective to explore the impact of such new technologies: they are only considered in isolation as disruptive technologies. Furthermore, the pathways that sketch out dietary change provide insights to better understand the notion of sustainable diets at a global and abstract level. They are less concrete when it comes to defining what this means on a regional level. Similarly, to what extent development of such pathways can be done while respecting local needs, context, and culture. A question left unaddressed in food systems science is what ethically can be demanded from more vulnerable communities in terms of dietary change.

Transformation of food systems requires action of all food system actors, across all regions. Acknowledged throughout the reports is that this will result in winners and losers, indicating the need to govern these processes for equitable conditions and outcomes. Here-with, equity is seen as a principal component of any strategy for sustainable food systems. To that end, many suggest global coordination of strategies in order to meet the needed sustainability objectives, while avoiding regional competition or hegemony of a single powerful region. Second, strong emphasis is put on development of accessible technologies and strategies, recognizing the large portion of the world population that could benefit from already existing, but currently expensive, technologies. However, as these food system perspectives fail to question the current economic and political systems that have led to the current situation in the first place, they rather assume it to result in the 'trickle-down' of equity. In other words, they fail to represent the major trade-offs faced in food systems that require hard decisions to be made regarding the prioritization of human well-being or ecological sustainability. The major concerning trends that are likely to affect equity considerations are signalled for consideration across some reports; nevertheless, systemic interpretation of their impacts is lacking. These concerns range from challenges related to ongoing concentration processes across the food chain, such as land acquisitions or mergers in the seed and retail sectors, to notions of moving agriculture to the most productive regions, i.e. linking agricultural production efficiency and conservation (ISPC 2018; FOLU 2019). All will threaten livelihood opportunities, particularly for smallholder farmers. Ultimately, this provides few insights on how to manage these trade-offs or who can be held accountable for correction towards potential 'losers' of processes of change.

5 Uncertainty, foresight, and research gaps

Addressing sustainability challenges in food systems is inherently future oriented and demands facing a high level of complexity and uncertainty. Recent forward-looking research reflects the use of foresight in uncovering pathways to sustainability, which shows the growing use of scenarios and foresight to deal with ‘unknowns’ (Stirling 2011; Saltelli *et al.* 2020). These approaches also unveil challenges for interpretation of diverse perspectives and system blind spots.

5.1 Assessing trends across the plurality of pathways

Along with a broader acknowledgement that food systems require transformation comes diverse framings of food systems. As a result, challenges identified in the food system also reflect this diversity and the diverse solution spaces to address these (Béné *et al.* 2019). In this paper, we attempted to unravel the diverse pathways that lie underneath the key trends and challenges in several food systems foresight reports. Comparing these diverse perspectives is challenging, as they are guided by different assumptions on what is ‘certain’ and what is ‘uncertain’ about the future in each of the outlined pathways. While this is part and parcel of many modelling exercises, transparency about these elements remains crucial to unravel what outputs require further nuance (Saltelli *et al.* 2020; Reid and Rout 2020).

The challenge is visible in the difference in boundary setting around food security when exploring the role of dietary change towards sustainability. Depending on one’s ambition, when setting out to ‘model’ food system futures, one has to make assumptions on the functioning of food systems. When food security is not seen as an element deemed uncertain (i.e. the ability to meet it), the results of both FOLU and EAT are relevant as their pathways assume food demand in terms of volumes can be met. This then allows for a greater focus on what the ecological boundaries of a healthy diet are, without taking into consideration how food security is met. WRI paints a rather different picture by regarding food security in the future as uncertain due to a further increase of population growth. As such, this pathway puts far more emphasis on the extent to which yield increases can be achieved. While equally offering sound forward-looking food systems approaches, these different pathways are difficult to compare based on the different assumptions made.

Another example that makes this visible is the extent to which *all* reports mention equity considerations amid a flurry of other key processes and drivers that shape food systems, but hardly put this element into a future or system perspective. As such, it becomes almost a static element in the system, rather than seeing it as a dynamic that is part of the system. Simply put, while equity is mentioned across the report, in terms of a foresight and food system perspective it remains a blind spot. As such, transparency on the assumptions that shaped the pathways of change is crucial, as it allows to understand what exactly was considered as a lever for change.

Embedded across these diverse perspectives of pathways are different understandings of sustainability and different prioritizations of sustainability elements (Béné *et al.* 2019; Eakin *et al.* 2017). Here, there is the potential that the ‘directionality’ of pathways of change does not line up, with the risk of exacerbating trade-offs towards the future (Stirling 2011). Key to uncovering these perspectives is to assess pathways of change through the proposed solution spaces and their underlying mechanisms of change and the extent to which they have considered the wider system. For example, left rather ambiguous is how to balance the objective to support the many livelihoods globally that depend on smallholder agriculture and the need for global coordination of land use that might require the re-allocation of food production to the most efficient places. While at first instance these pathways address objectives far apart, their paths could collide in the future, even resulting in a major trade-off. Besides conflicting outcomes between pathways, these could arise from within a single pathway. What stood out are the reports accentuating technologies that are considered promising for

food system sustainability, without assessing what future ramifications might be on other parts of the system. As such, disruptive technologies that serve a single purpose (e.g. quick gains in GHG emissions) run the risk of causing trade-off situations in the long run (reduced livelihood opportunities).

Related to boundary setting, there are differences in how the different studies understand and conceptualize what a ‘food system’ is and how it functions. This might be linked to a third issue when comparing the selected foresight reports, which are their differing framings of food systems, what activities they entail, and how they function. While many reports seemed to have some underlying assumptions of direct connections between producers and consumers, so that a change in agriculture would, for example, have direct implications for consumers, today’s food systems are very complex and comprise a multitude of actors in between (Ingram 2011; Ingram and Zurek 2018). The so-called missing middle (manufacturers, processors, retailers, etc.) and actions on their part that might be needed to enhance food system sustainability in the long term and the interplay across food system actors for that are little reflected in the reports and point to another blind spot.

5.2 Addressing foresight gaps and blind spots

While foresight can prove an effective tool in understanding food systems and informing how to address uncertainty and complex dynamics, there remain crucial research gaps and persistent blind spots. For future-oriented methods to align to societal needs, a number of concerns need to be addressed in future research and application of these methods.

While the reports are rich in exploring the impact of technologies on society and ecology, they lack reimagination of governance and economic dynamics. All pathways of change lean on the manipulation of ecological processes and societal dynamics through the already existing governance and economic structures. This is based on the belief that humanity can ‘control’ and ‘manipulate’ natural systems towards desired directions and opens up for pathways that feature ‘techno-fixes’ and overlook social–ecological dynamics (Brown *et al.* 2014). The roles of new policy instruments (such as taxes and price mechanisms), new governance arrangements, or other options for incentivizing food system change need to be explored with their implications in specific country settings.

There is a persistent blind spot when it comes to social dynamics around power and equity considerations across quantified future food system exercises. Partly, this is due to a difficulty to quantify certain elements such as underlying structures and associated power dynamics or concentration within supply chains (Lehtonen 2015; Lehtonen *et al.* 2016; Zurek *et al.* 2018), which can be attributed to unreliable or sporadic data. On the other hand, this is due to the challenges related to the translation of qualitative notions to ‘measurable’ units as they become a major source of contestation. Addressing this blind spot requires overcoming this challenge, either by supplementing the quantitative work with qualitative and participative input or by creating a participatory understanding of such social dynamics in food systems, which leads to the development of new indicators (Selomane *et al.* 2015). In general, however, addressing this challenge will require going beyond the assumptions that global coordination of policies and regulations will lead to improved outcomes, and taking deliberate effort to break down barriers of access and adoption of technologies and innovations (for a detailed analysis, see Lentz, [this issue](#)).

Across scientific work, there is a tendency to equate the complexity of climate change with the need to reduce GHG emissions. As such, ample solutions are offered that reduce GHG emissions. Meanwhile, less attention goes to some drivers that are considered immediate impacts of climate change, such as impacts on crops and livestock pests and diseases. Often obscured under the umbrella of climate adaptation for food systems, these are not discussed in detail. Especially as the majority of reports consider the likelihood of meeting the GHG emission reduction goals to be low, exploration of such more immediate impacts seems a

crucial topic to cover. While there is an absolute need for scenarios that sketch the pathways to desired and positive futures, they should also provide the tools and insights that allow assessing what happens when certain elements are no longer plausible.

The analysed reports mainly consider long-term trends while they explore in much less detail short-term disruptions and shocks. The current COVID-19 pandemic shows how quickly whole economies and with this their food systems can be disrupted. This also begs the question whether such crisis can trigger some of the needed transformations that the reports point out as needed to deal with the current failings of our food systems. The analysed reports, particularly those that developed scenarios, could be used for a deeper analysis of these issues, identifying some of the opportunities that different futures could (or fail to) provide to restructure food systems and their outcomes. As the reports nevertheless often lack a deeper discussion of plausible changes in food system governance, additional work in this area is needed. Nonetheless, the expectation that sudden shocks can help transformation towards sustainability should be approached with caution. The 2007–9 financial crisis deepened food insecurity, increased food prices, and disrupted the food systems around the world (von Braun 2008; Brinkman *et al.* 2010). Yet, 10 years after the crisis, the number of malnourished people has increased (FAO *et al.* 2018).

Lastly, across the reports a number of strategies are seen as promising levers for change, especially dietary change and (disruptive) technological innovations. While important in many pathways, they are often not fully analysed from a system's or spatial perspective. Here, regional differences or system connections could have major influence in distorting the expected impacts of these levers. This remains a major gap in food systems research and requires further investigation.

6 Conclusions: options for practitioners, policymakers, and donors to consider

The presented analysis of a number of foresight reports on possible food system change underscores the urgent need for a transition of food systems towards more environmental, social, and economic sustainability. At the same time, the complexity of today's food systems results in large uncertainties about how the drivers of food system change interact and how their interactions will continue in the future. A wide range of drivers are identified as shaping food system outcomes and as potential levers for change: climate change, environmental issues, technological change, societal changes, market dynamics, and governance dynamics. A plethora of responses exist to address these food system drivers, most of which are geared towards specific impacts on specific food system activities, thus sometimes overlooking their implications in a system's context.

Looking across the reports, a number of key interventions emerge that different actors in the food system together with policymakers and donors can consider to incentivize the need transformation of our food systems:

- *Adaptation needs to keep pace with climate change:* The need for adaption to climate change impacts is underscored in the foresight reports. Adaptation measures are considered crucial to maintaining our ability to feed a growing world population. The question remains whether current efforts can keep up with expected impacts across countries and agro-ecological zones.
- *Navigating adaptation and mitigation challenges:* While adapting to climate change is essential, agri-food systems have an important role to play in the future in climate change mitigation. The foresight studies show growing GHG emissions from the sector if current trends continue, which is incompatible with reaching the Paris Agreement targets. Addressing adaptation and mitigation needs will require a careful balancing act in many countries, particularly of the Global South with respect to finding

solutions and channelling scarce resources into a mix of options that can also maintain and enhance food security levels. For this, a prudent navigation of priorities, new technologies, and incentive structures will be needed.

- *Space to foster debate:* The road to sustainable food systems in the future is riddled with trade-offs and tough decisions across the goals that different food system actors might have. This requires coordinated efforts to address the difficult choices and a safe space for decision-makers to debate different options and assess who might win and who might lose (McKeon 2015; Pereira *et al.* 2019). Finding solutions in a way that includes marginalized voices in the debate will be key for transitioning towards equitable and economically sound food systems.
- *Context and culturally sensitive change towards healthy and environmentally friendly diets:* The need for a global shift towards healthier and environmentally friendlier diets is shown across the analysed studies. Many reports discuss this at a global scale and portray the need for more plant-based and diverse diets, including higher quantities of vegetables, fruits, and nuts. This analysis, though, does not take food culture or socioeconomic contexts into account, nor does it reflect on geographic differences that might lead to a differently composed diet. More research and innovation are needed on how to contextualize these globally determined diets, making them sensitive to local cultures, ecosystems, and resource availability.
- *Innovation in sustainable protein production:* The reports discuss the need for protein sources that are healthy while having low environmental impacts. In the context of this debate, there is the need to think about alternative protein sources in addition to more traditional improvements of livestock practices.
- *Trade-off analysis/anticipation:* As emphasized before, the key food system goal of food and nutrition security must be pursued in coordination with additional goals for food system management: environmental sustainability, livelihood opportunities, and equity considerations. Doing so requires tools and brokering spaces for trade-off analysis across goals and food system actors in different social contexts, as well as foresight methods and tools that help to explore new choices (Galafassi *et al.* 2017). Foresight work, especially if done on a regular basis to aid with priority setting, could be used in a coordinated manner both within CGIAR and with different country partners to help align strategy and research investments across the major topics of concern identified by all partners.
- *An integrated menu of options:* The scenario analyses carried out in the WRI and FOLU reports point to an integrated menu of options for meaningful food system change. This approach requires thinking through and contributing to necessary innovations in the food system with a view to how changes in agriculture relate to changes in other food system activities—food processing, food storage, retail, food consumption, etc. For this, an overall food system perspective is needed so that an integrated set of options for change across the system can be developed.

While the importance of future food systems research is broadly acknowledged, future research needs to focus on a number of common blind spots and gaps as outlined in Section 5. We argue these are vital for forward-looking food systems research to inform decision-makers on how to steer food systems into a more sustainable direction that brings everyone along.

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Table A2. Environmental drivers of food system change, their trends, and associated pathways for food system change.

Food system drivers	W	E	F	G	A	N	H	L	P	E	R	I	W	Proposed pathways for food system change	RethinkX	F	O	L	U	R	I	W	I	S	I	P	P	O	RethinkX		
Current trends in drivers	•	•	•	•	•	•	•	•	•	•	•	•	•																		
Water pollution														Manure management																	
Water scarcity	•													Innovative fertilizer																	
Nutrient scarcity	•													Improved water management																	
Land use competition (e.g. conservation and urban sprawl)														Phasing out of bioenergy																	
Land grabbing														Protection of natural landscapes																	
Biodiversity loss (agro-wild)														Designation of efficient agricultural zones																	
														Identification of marginal agricultural lands for reforestation																	

(Continued)

Table A2. (Continued)

Food system drivers	W	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	
Current trends in drivers	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Proposed pathways for food system change	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Integration of native species in reforestation																								
Extension of payments for ecosystem services																								
Extension of deforestation-free supply chains globally																								
Global investments in reforestation																								
Regenerative agriculture																								
R&D in soil and water management																								
Incentives for regenerative agriculture																								
Reforms in natural resource governance and tenure																								

(Continued)

Table A3. Societal drivers of food system change, their trends, and associated pathways for food system change.

Food system drivers	W E F	G A I N	H L P E	W R I I	G K I	F O L U	I S P C	W I P O	RethinkX	Proposed pathways for food system change	W E F	G A I N	H L P E	W R I I	G K I	F O L U	I S P C	W I P O	RethinkX
Societal changes																			
Dietary change	•						•			Policy options to influence diets									
Financing for SMEs offering healthy and sustainable food										Financing for SMEs offering healthy and sustainable food									
Public procurement of healthy and sustainable food										Public procurement of healthy and sustainable food									
Personalized nutrition										Personalized nutrition	•								
Influence on purchasing decisions										Influence on purchasing decisions									
Increased offerings of alternative proteins										Increased offerings of alternative proteins									

(Continued)

Table A3. (Continued)

Food system drivers	W E F	G A I N	H L P E	W R I	G K I	F O L U	I S P C	W I P O	Proposed pathways for food system change	W E F	G A I N	H L P E	W R I	G K I	F O L U	I S P C	W I P O	RethinkX
Current trends in drivers									Effective marketing of healthy and sustainable foods									
Increasing demographic imbalances									Improved women's education									
Growing urbanization									Improved reproductive health care									
Increasing migration									Zoning to limit competition from urban encroachment									

Table A4. Market dynamics as drivers of food system change, their trends, and associated pathways for food system change.

Food system drivers	Current trends in drivers	W E F	G A I N	H L P E	W R I	F O L I	I S P C	W I P O	Proposed pathways for food system change	H L P E	W R I	F O L I	I S P C	W I P O	RethinkX
Market dynamics	Market-designed innovations								Accessible and sustainable innovations						
	Fair food commerce								Managed food prices						
	Finance for green technologies								Transparency in the food supply chain						
									Investment in climate-smart technologies						
									Investment in close-the-loop technologies						
									Corporate targets for food loss and waste reduction						
									Support for displaced workers of phased-out industries						
	Growing influence of emerging economies														

Table A6. (Continued)

Food system drivers	W	E	F	G	A	N	H	L	P	E	I	R	W	G	K	I	F	O	L	U	C	P	O	W	I	S	P	P	O	RethinkX					
Current trends in drivers	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•				
Renewable energy innovations	•																																		
Convergence of information and biotechnology Big Data and AI for food	•																																		
Proposed pathways for food system change	•																																		
Scale up renewable energy and make it broadly accessible																																			
Precision fermentation to engineer proteins																																			
Precision agriculture																																			
Open access to public sector data																																			
Expansion of mobile service delivery for farmers																																			
Insurance for farmers																																			
Virtual farm-to-fork																																			
market-place supply chain for trans-parency and traceability																																			
Real-time supply chain for trans-parency and traceability																																			
Internet of Things																																			

Table A7. Scenario assessment of key food system outcomes in 2050 compared with current status.

Key food system outcomes	WRI			FOLU			WEF			EAT		
	Base-line	Coor-dinated effort	Highly ambitious	Break-through technologies	Current trends	Better futures	Survival of the richest	Unchecked consumption	Open-source sustainability	Local is the new global	BAU + full waste	PROD+ + diet shift + half waste
Food and nutrition security												
Availability	++	+++	++	++			+++	+++				
Total food production												
Yields												
Food loss and waste												
Food imports												
Utilization												
Food quality												
Nutritional health												
Food price volatility												
Stability												
Socioeconomic shocks												
Food affordability												
Food distribution (national, local, and household)												
Self-sufficiency												
GHG emissions												
Climate change												
Environmental sustainability												
Biophysical seasonal changes												

(Continued)

Table A7. (Continued)

Key food system outcomes	WRI			FOLU			WEF			EAT		
	Base-line	Coor-dinated effort	Highly ambitious	Break-through technologies	Current trends	Better futures	Survival of the richest	Unchecked consumption	Open-source sustainability	Local is the new global	BAU + full waste	PROD+ + diet shift + half waste
Outcome variables												
Extreme events												
Freshwater quality												
Status of land resources												
% freshwater availability for food systems	-	-	+	++	o	++	---	---	+	+	---	+
Nutrient cycling												
Soil quality	+	+	++	+++	-	++	---	---	+	+	---	+
Agricultural land use	+++	+	--	---	+++	--	++	++	+	+	+++	---
Land fragmentation	+	-	--	---	+	---	---	---	---	-	++	---
Wild biodiversity	o	+	++	+++	---	++	---	---	+		---	-
Agrobiodiversity	+	+++	+++	+++	-	++	---	---	+		---	
Wild marine biodiversity	+	+++	+++	+++	-	++	---	---				
Aquaculture production	+	++	+++	+++	++	+	---	---				

(Continued)

Table A7. (Continued)

Key food system outcomes	WRI			FOLU			WEF			EAT			
	Outcome variables	Base-line	Coor-dinated effort	Highly ambi-tious	Break-through tech-nologies	Current trends	Better fu-tures	Survival of the rich-est	Unchecked con-sump-tion	Open-source sus-tain-abil-ity	Local is the new global	BAU + full waste	PROD+ + diet shift + half waste
Economic and social well-being	Number of jobs in food systems					0	++	---					
	% of GDP from food systems							---					
	Farmers' income from food system activities					-	+	---	+	+	+		
Equity considerations	Gender					0	+	---					
	Balanced relationships between Global South and Global North					0	+++	---	+				
	Land tenure					0	++	---	---				