Synthesis

Food and Agriculture Systems Foresight Study

Implications for climate change and the environment

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Complex Systems in Transition

About this synthesis

This synthesis on Food and Agriculture systems foresight studies was commissioned by the Independent Science for Development Council of CGIAR as input for CGIAR's research strategy to 2030 and the new *One CGIAR*.

CGIAR | Independent Science for Development Council

Two desk studies were commissioned: this one, which focuses on implications of recent foresight studies for CGIAR research for development as it relates to the One CGIAR impact areas of climate change and environment. A second commissioned study focuses on the implications for the impact areas nutrition, poverty and gender.

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Executive Summary

The linkages between food systems, the environment, and climate change are complex and in constant flux. Food systems rely on the environment for inputs such as land, water, and genetic materials. At the same time, poor management of agricultural land, freshwater, and marine resources and the continuing expansion of agricultural land are the biggest threats to environmental health. Furthermore, agriculture and food systems are responsible for a considerable proportion of global greenhouse gas (GHG) emissions. This reciprocal relationship means that environment and climate change shape the future of food systems while food systems have impacts on the environment and climate change. These changes do not take place in isolation but are inseparable from other key factors such as technological change (especially disruptive technologies and technology adoption), societal changes (such as dietary change), market dynamics, and ways to govern food system activities.

The presented synthesis of food foresight studies was commissioned by the Independent Science for Development Council (ISDC) of CGIAR as part of the ongoing reform process of the system toward One CGIAR. The study focuses on 'the implications of recent foresight studies for CGIAR research for development as it relates to impact areas of climate and environment'. The desk review synthesizes a set of 11 key documents selected by the ISDC. The reports vary substantially in their specific foci and the parts of food systems they address (e.g., agriculture, value chains, consumers). In addition, several of them focus on specific food system developments (such as technological advances) and their effects. While several reports portray the main forces shaping future food systems and their trends, four reports also present plausible futures showing varying patterns of food system driver interactions. A food systems approach was used for a comprehensive analysis which sees climate and environmental change as important drivers of change but also as outcomes of food system management.

Climate and environmental issues

Climate change and environmental issues related to water, biodiversity, soils, and nutrient cycling are seen by the analysed reports as the most important drivers changing food systems. To halt climate change, reports highlight the needed contribution of food systems to reduce GHG emissions in both developed and developing countries. This will require hard decisions regarding prioritisation of food system outcomes. The synthesis points to the continuing need to adapt to expected changes in climate. While the reports focus primarily on the agricultural sector, other food system activities – such as transport, storage or retail – will also have to adapt. Nevertheless, high uncertainty remains about the extent to which adaptation can offset climate impacts and what impacts insufficient adaptation might have, particularly on the more vulnerable parts of society. Based on this uncertainty, the reports point to the need to increase mitigation efforts in food systems. This requires careful navigation of priorities of different countries, development of new technologies, and incentive structures.

Nearly half of the terrestrial land globally is used for agriculture, which is one of the biggest drivers of environmental degradation. Growth in food demand and poor land management will continue to put pressure on environmental resources, such as water, biodiversity, soils, and nutrients. Considering the importance of these resources as inputs into food systems, their continued degradation will have serious consequences for meeting increasing food demands. Some of the reports caution against overapplication of fertilisers, which have negative water quality implications, while others highlight the loss of crop diversity, mirroring biodiversity loss. Emphasised as crucial are sustainable water and soil management and restoration of natural landscapes.

Technological innovations

All reports see technological innovations as a key part of the solution space for food system change. These innovations are needed across the entire food system, from the agricultural system to changes in consumer behaviour: Some reports show how innovations in one part of the system should be coordinated with other parts of the food system. They also stress the need for these innovations to be accessible and affordable, signalling equity concerns. Throughout the reports, both disruptive and incremental innovations are proposed. The reports raise questions on how to best govern and coordinate innovation systems, including research funding, so that they provide wide access to new technologies.

Dietary change

Dietary change addresses both nutritional and sustainability concerns. Improving nutrition, rather than only meeting caloric needs, is considered key to addressing the triple burden of malnutrition. Healthy and balanced diets need to include more fruits, vegetables, and nuts. For more sustainable diets, a move towards reducing meat intake and increasing alternative protein sources is necessary. The studies paint an aggregate picture of what constitutes dietary change at a global level but are less clear about what this might mean on a regional and country level.

Just transitions

The ability of food systems to deliver food and nutrition security outcomes in an equitable manner is underscored across several reports. However, they do not elaborate on how this can be achieved, such as how to support those impacted negatively by change processes. The ongoing concentration of markets and other processes in the food sector have further contributed to inequity in the food system. This remains a major gap in these food system studies.

Key recommendations for CGIAR

CGIAR could play different roles in addressing the future food systems challenges identified in the analysed reports. CGIAR is well positioned to address some challenges within its current set of activities, while others would require extending or reshaping its focus.

1) CGIAR has longstanding experience with developing adaptation practices. It needs to continue its work on adaptation and support innovation processes to keep up with expected climate change impacts. Moreover, CGIAR can contribute to the development of more contextual pathways to adaptation measures, as this cannot be done via a global blueprint.
2) With respect to balancing adaptation and mitigation options for the food sector, knowledge and insights into the country context are needed as well as an understanding of biophysical dynamics and technology options. CGIAR is well positioned to support country partners in exploring difficult choices and to adjust innovation systems for developing appropriate technologies and policy options.
3) Based on CGIAR's long-standing relationships with a wide range of food system actors, the organisation can convene and foster much-needed debate on contentious issues and trade-offs prevalent in current and future food systems with existing and new partners.
4) A focus on better nutrition can offer new opportunities to CGIAR while balancing its current focus on staple crops. CGIAR can contribute to addressing the knowledge gap on how to contextualize dietary shifts in a manner that is ethically and culturally appropriate. This could build on CGIAR's experiences around nutrition and land use management. There is also an opportunity for CGIAR to expand towards an investigation of new sources of protein from fish and mariculture as well as plant-based sources. Here the reach and experience of CGIAR in implementation of programs would provide the infrastructure needed to make these techniques accessible.
5) CGIAR could provide foresight and trade-off analysis tools and methods as well as space for dialogue internally and for different partners – for example, linked to further activities of the Global Futures program or of the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). This could be done on a global level or on a country or regional level to enable coordinated strategies across multiple partners and CGIAR.
6) For CGIAR, a food system perspective can shape a comprehensive research agenda to foster coordinated food system transformation. This would also allow CGIAR to expand the set of partners it works with in research and priority setting.

1. Introduction

1. Introduction

Agriculture and food systems are in constant flux, and food systems today include the wider considerations of food and nutrition security as well the environment, health, the economy, and equity. This wider notion of agriculture and food in relation to other systems opens avenues for systems thinking in current and future food systems. Despite the growing appreciation of the complexity of agri-food systems, many interrelated challenges obscure how to transform the food system towards environmental, economic, and social sustainability.

Current food systems have not met 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 undernourished – in fact the number of people increased from 2015 to 2016 (FAO 2017). This problem will continue to worsen unless drastic actions are taken (Foley et al. 2011). The projected population growth towards 9 billion people in 2050 and the expected changes in diets which are facilitated by increasing levels of income will add to this challenge. Further pressure is added by a growing demand for resource-intensive foods such as meat owing to ongoing dietary change facilitated by growing incomes. In addition, the current agri-food system does not always produce the *right* food. This is reflected by increases in diet-related health issues (Clark et al. 2018, 2019), non-communicable diseases, and obesity, coexisting with stunting and wasting in many countries. Together these challenges are termed the 'triple burden of malnutrition'.

Food systems and the environment

There is now overwhelming appreciation of the ways agriculture and food systems are linked with environment and climate change. On one hand, food systems rely on the environment for inputs such as land, water, and genetic materials for crop diversity (Dawson et al 2019; Willet et al. 2019). There is increasing competition for these resources with other sectors in society, and most, such as water, are stressed, overallocated, or in short supply depending on the region. On the other hand, agricultural expansion is the biggest threat to environmental health (Foley et al. 2011; IPBES 2019). For example, the use of nutrients such as nitrogen for fertilizer, while instrumental for increasing yields, is also causing pollution to water ecosystems, and unsustainable land management is resulting in land desertification (IPBES 2018). Similarly, land use for agriculture is reducing habitat for biodiversity and causing biodiversity loss. This relationship has spurred many studies investigating how to minimize the trade-offs between various resources through nexus approaches (Simpson and Jewitt 2019; D'Odorico et al. 2018; FAO 2014) that serve as a starting point towards a systems approach.

Climate change is a major driver behind many challenges in the food system in two main ways. The first is through the physical changes in climate variables, which also threaten the stability of the climate system. By raising the unpredictability of precipitation and growing seasons and increasing floods and droughts, climate change will continue to have major impacts on the agri-food system, as temperatures are projected to increase in all major climate models. The second is through the impacts of solutions proposed to mitigate climate change. With the food sector responsible for around a quarter of all GHG emissions (Vermeulen et al. 2012) – mainly resulting from livestock farming, fertilizer use and production, energy use in agriculture and supply chains, and rice production – food systems are now called upon to reduce their emissions profiles. Mitigation strategies rely on large-scale application of bioenergy with carbon capture and storage, as well as afforestation, which often compete with food production for land (Van Vuuren et al. 2018). Furthermore, the rise in the number of vegetarians and vegans in the last few years shows the growing consumer awareness of the climate change impacts of livestock systems. Changing consumption patterns towards healthy and balanced diets together with a reduction in food loss and waste are now seen as major levers of change towards more climate-friendly food systems (e.g. Willett et al. 2019).

CGIAR reform

CGIAR is undergoing a reform process towards One CGIAR, bringing its 15 international research centres into a new structure and revisiting its priorities. The aim of the process is to streamline the different functions of the organization under a unified vision. This study was commissioned by the Independent Science for Development Council (ISDC) of CGIAR as part of this reform process. The study focuses on 'the implications of recent foresight studies for CGIAR research for development as it relates to impact areas of climate and environment'. The desk review focuses on a set of key documents (see **table 1**) selected by the ISDC, including reports from the Independent Science and Partnership Council of CGIAR, the World Economic Forum (WEF), High Level Panel of Experts on Food Security and Nutrition (HPLE), Global Alliance for Improved Nutrition (GAIN), World Resources Institute (WRI), Food and Land Use Coalition (FOLU), World Intellectual Property Organization (WIPO), and RethinkX (see table 1 for a complete overview, and see the annex for the terms of reference). The reports vary substantially in their specific foci and the parts of the food system they address. In addition, several of them focus on specific food system developments (such as technological advances) and their effects. This synthesis report did not systematically identify other foresight studies related to food systems and environmental issues. Particularly in recent years there has been a proliferation of forward-looking work in this area; Wiebe et al. (2018) identified 3,161 articles in SCOPUS, published between 2013 and 2017 alone, that included the keywords 'uncertainty', 'scenario', and 'future'.

In this paper we first provide in Section 2 a short overview of the food system concept as applied in the analysis as well as a short description of forward-looking approaches, particularly of scenario planning as the main foresight methodology used in the analysed studies. Section 3 describes the key drivers of change in food systems as presented in the analysed reports, with a focus on climate change and environmental issues. Section 4 presents the results of looking across food system change scenarios as described in some of the analysed studies and their implications for food system outcomes (food and nutrition security, environmental outcomes, and socioeconomic outcomes). In Section 5 and 6 we describe the main findings when looking across the analysed drivers and scenarios for the work of CGIAR in the climate change and the environment impact areas.

Table 1. Overview of the forward-looking documents on food systems change considered in this synthesis report

Title of document	***Institution***	***Year***	***Food system focus***
Growing better: Ten critical transitions to transform food and land use	Food and Land Use Coalition	2019	Full food system
Nutritious food foresight: Twelve ways to invest in good food for emerging markets	Global Alliance for Improved Nutrition and Global Knowledge Initiative	2019	Innovation for nutrition security
Innovating the future of food systems: A global scan for the innovations needed to transform food systems in emerging markets by 2035	Global Knowledge Initiative	2017	Supply chain innovation
Food security and nutrition: Building a global narrative towards 2030	High Level Panel of Experts	2020	Food security and nutrition
Agriculture & food systems to 2050: Global trends, challenges and opportunities	Independent Science and Partnership Council	2018	Full food system with focus on agriculture
Science breakthroughs to advance food and agricultural research by 2030	The National Academies Press	2019	Food system with focus on agriculture and nutrition
Rethinking food and agriculture 2020-2030: The second domestication of plants and animals, the disruption of the cow, and the collapse of industrial livestock farming	RethinkX	2019	Alternative protein production
Innovation with a purpose: The role of technology innovation in accelerating food system transformation	World Economic Forum and McKinsey & Company	2018	Food system
The global roots of innovation in plant biotechnology	World Intellectual Property Organisation	2019	Food Production
Creating a sustainable food future: A menu of solutions to feed nearly 10 billion people by 2050	World Resources institute	2019	Full food system
Food in the Anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems	EAT–Lancet Commission	2019	Food system focus

2. Food systems & foresight work

2. Food systems and foresight work

In this section we explore the key concepts used for the analysis of the selected foresight studies. This includes a description of the food system concept used for the analysis and a brief overview of forward-looking work, particularly scenario planning.

2.1 A food systems lens to analysing food, climate change, and environment interactions

We use a food systems approach to analyse the implications for food systems of possible climate change trajectories and changes in the environmental variables. In this systems view, changes in climate and the environment are seen both as key forces driving food system change and as outcomes of how food systems are managed.

The food system is made up of several food system activities, including primary production, processing, retailing, and consuming, along with storage and waste disposal (see **figure 1**) (Ericksen 2008; Ingram and Zurek 2018). These activities are undertaken by different actors, all with their own sets of incentives and motivations. In reality, food systems involve multiple interacting value chains.

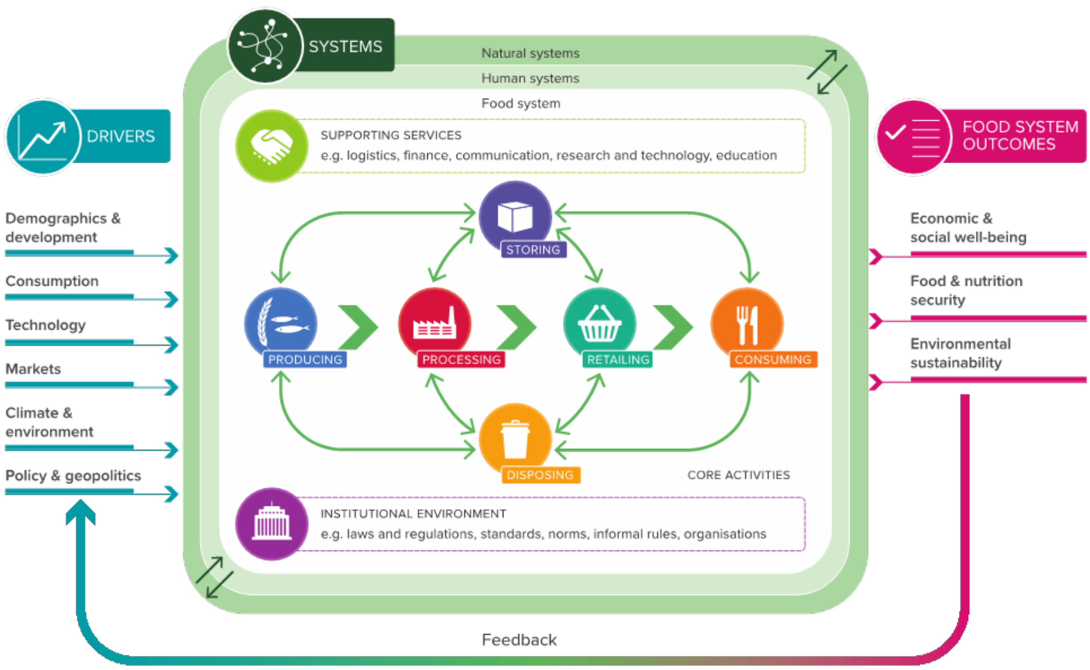

Figure 1. A conceptual model of a food system (www.foresight4food.net)

The food system operates within and depends on a wider context of human systems and natural systems with multiple interactions and feedback loops (Zurek et al. 2018). The wider systems create a set of external driving forces, each with specific trends, that shape the behaviour and evolution of the food system. Each actor in the system is influenced differently and thus reacts differently to this confluence of factors. There exist a wide range of drivers of food system change such as demographic developments, wealth distribution, consumption preferences, technological developments, markets arrangements, politics, and climate and environmental factors. Drivers of change provide one of the key entry points to manage food system change. These drivers can be manipulated to move the system onto a different trajectory. The other entry point for change in the food system is to reconfigure the relationship between the system elements – i.e., the food system actors and their activities – by, for example, shortening value chains by direct marketing of produce to consumers via farm shops.

The outcomes of food systems can be categorised into three main areas: food and nutrition security, economic and social well-being, and environmental outcomes. While food systems provide many livelihood opportunities both in developed and developing countries, they currently do not deliver the expected food and nutrition security outcomes (i.e., there is a triple burden of malnutrition). There are also increasing social inequalities embedded in food systems, including unequal access to food, markets, and technological innovations. Additionally, food systems are one of the major contributors to global environmental change (Folet et al. 2011; Garnett 2011; McKeon 2015).

2.2 Dealing with the future in complex system contexts

Food systems involve the interplay of human and natural systems and as such are complex adaptive systems. This means they contain high degrees of uncertainty and may evolve in ways that cannot be entirely predicted and controlled. A number of tools exist to explore complexity and uncertainty about the future to aid decision making, such as trend analysis and trend extrapolation, forecasting (e.g., Armstrong 2001), cross-impact analysis (e.g., Gordon and Hayward 1968), futures workshops (e.g., Jungk and Müllert 1987), Delphi-type expert-based estimates (e.g., Helmer 1983), role playing, gaming and simulation (Vervoort 2019), and future state visioning (e.g., Stewart 1993), as well as the development of future histories, science-fiction writing (Merrie et al. 2018), and even wild speculation.

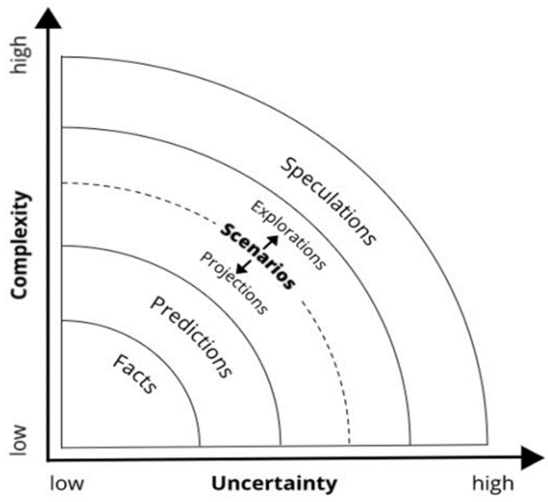

Figure 2. Foresight approaches to explore uncertainty in complex systems (Zurek and Henrichs 2007).

In many decision-making contexts, scenario planning has emerged as a widely used method across different communities for exploring how driving forces might shape the future, for developing strategies robust to different ways the future might play out, and/or for entering into tailored strategic conversations with decision-makers about difficult choices and trade-off decisions. Rooted in military planning exercises of the Second World War and the Cold War, scenario analysis was later taken up by the business community (such as the Royal Dutch Shell scenarios group), used for conflict mediation processes (such as the Mont Fleur Scenarios about the abolition of apartheid in South Africa), and then found its way into the environmental assessment community, such as the Intergovernmental Panel on Climate Change (IPCC), the Millennium Ecosystem Assessment, the United Nations Environment Programme's Global Environment Outlook (GEO) assessments, the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD), and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).

Various definitions of scenarios exist. The Millennium Ecosystem Assessment defines scenarios 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). Nearly all definitions have in common that scenarios explore a range of plausible future changes, and they usually stress that scenarios are not predictions, forecasts, or attempts to show the most likely estimates of future trends (**figure 2**). Scenarios also explore differing patterns of interactions between the key drivers of change (**figure 3**).

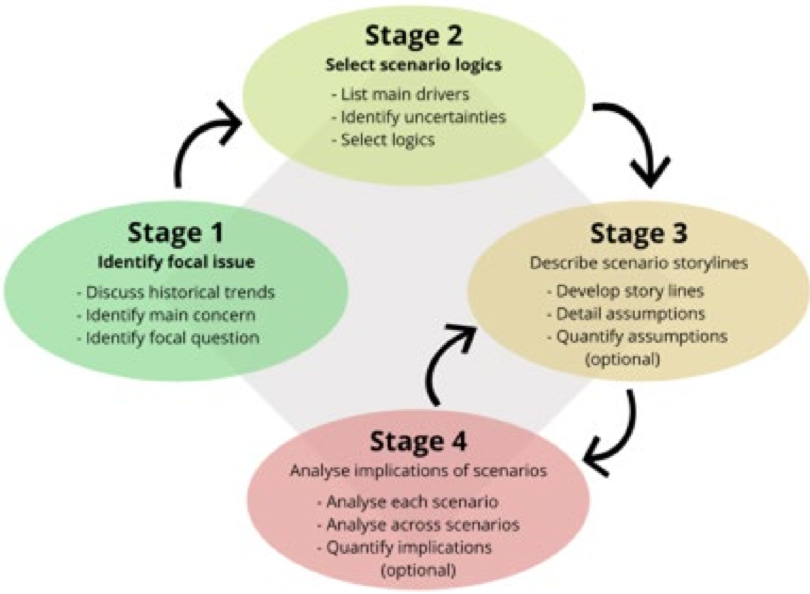

Figure 3. Stages of a scenario development process (Ash et al. 2010)

Exploratory scenarios start from the present and explore the impacts of various drivers, trends, and interactions from now into the future. Normative scenarios start from a particular vision of the future and work their way backwards to identify pathways for reaching this future. But this basic classification is not universal, and debates continue about distinctions between scenarios and their qualitative and quantitative framings (Wiebe et al. 2018). 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). Simply put, 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.

2.3 Analytical approach

This synthesis uses a food system lens to assess all foresight reports while looking for proposed pathways of change to further sustainability transitions. It next provides a cross-report analysis of both trends and pathways of change, to produce a more robust vision of pathways toward sustainability (Leach et al. 2011).

Diverse perspectives to change

The food system's complexity not only presents many challenges and uncertainty, but also opens space for different ways of looking at the system (Eakin et al. 2017; Béné et al. 2019). Crucial here is that different ways of perceiving the system generally lead to seeing different *root causes* to problems in the system and different *solutions* to address them. This results in a plethora of pathways of change (Stirling 2011), each arguing for change via a different route, based on different drivers or relations in the system. It is essential to unravel these different perspectives on change, as multiple and different pathways of change are put into motion globally. Here there is the risk that certain pathways might cross each other, and instead of complementing each other, they might hinder each other's progress. Better understanding of these different perspectives on (or narratives of) change will better equip actors to govern sustainability transitions (Loorbach et al. 2017) and deal with the uncertainty embedded in future pathways.

Proposed pathways to change

To assess these different pathways of change, we first explore the role of climate change and environmental issues as drivers of food system change and synthesise the report findings in a trend analysis. We also include an overview of the additional main drivers of food system change (i.e., governance, markets, technology, and societal dynamics) because they interact with climate change and environmental dynamics in each of the food system activities and will jointly shape what the food system will look like in the future.

Across the reports, different pathways of change are proposed to address food system trends. These pathways intend to find measures that either change the direction and intensity of the described trends, or change the interactions among drivers as a way to steer food systems in the desired direction. Here the tables highlight the range of different pathways that are proposed in addressing these trends, showcasing the plurality of perspectives across the reports.

This is followed by an exploration of impacts of the potential food system changes. This is analysed by assessing their performance with respect to the key food system outcomes, namely environmental sustainability, food and nutrition security, and economic and social well-being. These correspond with the five impact areas of CGIAR as shown in **figure 4**. In the synthesis we focus on similar results across the scenario analyses pointing to future changes that seem inevitable. There are nevertheless various differences between the scenario results based on different assumptions made by the report authors.

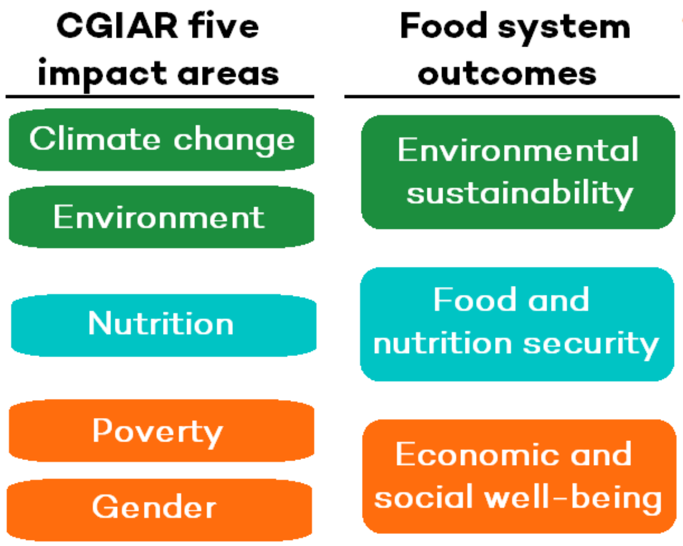

Figure 4. GIAR impact areas linked to the key food system outcomes

Guiding forward-looking questions

Based on the trend analysis and the synthesis of scenario results, we summarize a set of key findings on future trends and challenges that policy- and decision-makers will have to consider in the future. We also highlight gaps in the analysed foresight reports that point to the need for research. Furthermore, we draw conclusions for the work of CGIAR. For this we use a number of guiding questions to reflect on the role of CGIAR across the plausible futures portrayed by the analysed reports:

- How do CGIAR roles differ across the trends and scenarios?
- What could be new focus areas of work for CGIAR, and what should be the balance with current focus areas?
- What would CGIAR have to change to remain relevant over the next 30 years across scenarios and trends?
- How can CGIAR as an organisation be robust across the described plausible futures?
- Are there plausible futures without a role for CGIAR?

3. Main forces driving food systems in the future

3. Main forces driving food systems in the future

Food system change is driven by a wide range of different forces, including environmental, social, economic, technological, demographic, and political drivers. A 'driver of change' was defined by the Millennium Ecosystem Assessment as 'any natural or human-induced factor that directly or indirectly causes a change in a system' (MA 2003). Drivers interact in various ways with each other and impact the diverse actors in the food system in differing ways. Some of the forward-looking exercises, particularly scenario planning, explore these interaction patterns in a systematic way, looking both at existing patterns and at newly emerging ones.

In this section we synthesise the studies' findings of the main forces driving food system change, with a particular focus on climate change and environmental issues. We also highlight the pathways identified in the studies to respond to these drivers (**tables 2-8)**. Different studies provide different answers to the challenges and opportunities that each driver might pose based on the authors' conceptualization of the food system. In the annex we also provide a summary of the proposed innovations in each food system activity from each report. What the proposed responses do not reveal is the wider systems context within which these interventions 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 Climate change

There is a large amount of analysis available on climate change and food system interactions (see for example the Food and Climate Research Network, FCRN.org.uk), and all the analysed exercises identify climate change as a key driver of food system change. How the impacts of climate change on food systems are described and what parts of the food system will be affected differ. However, the exercises agree both on the need for food system activities to adapt to the potential changes posed by climate change and on the need for climate mitigation actions in the food sector.

The reports distinguish between three different trends that impact food systems (**table 2**): Changes in physical climate variables (e.g., changes in mean temperatures), the rise in extreme events affecting agriculture and the rest of the food system, and the rising GHG emission profile of the food sector and the associated need for mitigation actions. Climate change will also affect elements of the food system beyond the farm, including economic risks to elements of the value chain such as storage facilities, processing plants, and transportation, as well as political risks should government policies shift toward or away from environmental sustainability.

Changes in physical climate variables

The ISPC book defines mean climate changes as 'the amount by which mean climate change variables (e.g., temperature, precipitation, sunlight, winds, relative humidity) are altered by the global climate

Table 2. Climate change variables as drivers of food system change

Food system drivers	Current trends in drivers	WEF	GAIN	NAP	HLPE	WRI	GKI	FOLU	ISPC	WIPO	RethinkX	Proposed pathways for food system change	WEF	GAIN	NAP	HLPE	WRI	GKI	FOLU	ISPC	WIPO	RethinkX
Climate change	Changes in physical climate variables *(e.g., temperature, precipitation, wind, sunlight)*					●		●	●		●	Breeding of crops and livestock with adaptive traits					●				●	
												Modified land management practices					●		●			
												Reduced irrigation-based agriculture					●		●			
	Increase in GHG emissions	●	●			●	●	●	●		●	Fossil fuel–free innovations	●	●			●	●	●			
												Peatland restoration					●		●			
												Innovative ruminant feed					●					
												R&D on low-emission rice varieties and management					●		●			
												R&D on reducing manure emissions					●		●			
												Policy incentives for managed manure systems					●					
	Increase in extreme events					●		●	●			Disaster support systems							●			
												Early warning systems *(e.g., for pests, diseases, weather)*						●				

change signal' (chap. 5). 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). Temperature changes will affect crop yields in most parts of the Global South negatively while some areas in the Northern Hemisphere might gain (WRI 2019). The ISPC book states that surface warming is amplified at high latitudes owing primarily to feedback associated with melting snow and ice, as well as at higher elevations and in arid regions where excess energy is more efficiently transferred into near-surface heat. Many of these most rapidly warming areas have little agricultural production at present. Increases in daily minimum (night-time) temperature appear to be outpacing the warming of daily maximum temperature, resulting in an uncertain reduction in diurnal temperature range that may lead to night-time crop respiration stresses. Large-scale trends noted by the IPCC (Hartmann et al. 2013), however, have largely exacerbated historical patterns by making wet areas wetter and dry areas drier (Trenberth 2011; ISPC 2018). Higher temperatures are expected to enhance the overall water cycle, but thus far increases in atmospheric moisture have tracked increases in saturation limits, resulting in nearly constant relative humidities (Hartmann et al. 2013). Changes in photosynthetically active radiation (PAR) are also uncertain, as climate shifts affect different types of clouds, and the circulation patterns that steer them, in unique ways (ISPC 2018). The ISPC provides a picture of the main mechanisms by which changes in climate variables directly impact cropping systems (**table 3**). The analysed reports provide a number of responses to the potential changes in physical climate variables, such as adaptive breeding strategies for crops and livestock or changes in land management practices, but they are by no means exhaustive.

Table 3. Main drivers and mechanisms for direct climate change impacts on cropping systems (source: Ruane and Rosenzweig 2018)

Climate driver	Biophysical mechanism	Overview of direct impact on agriculture
Increased mean temperatures	*Accelerated maturity*	Warmer temperatures cause plants to develop at an accelerated pace, leading to an earlier maturity before sufficient biomass has been gained and therefore reducing overall yield.
Increased mean temperatures	*Shifts in suitable growing seasons*	Warmer temperatures generally extend the growing season in areas that are currently limited by cold temperatures while restricting growing seasons in regions limited by high temperatures.
Extreme temperatures	*Heat stress, leaf loss, and mortality*	Extremely hot temperatures cause plants to reduce photosynthetic activity, with prolonged exposure leading to leaf loss and potentially full crop failure (Asseng et al. 2015).
Heat wave during flowering stage	*Pollen sterility*	The impacts of heat waves depend on a plant's developmental stage; heat waves during flowering (antithesis) can cause pollen to be sterile, leading to reproductive failure and low grain numbers.
Elevated CO_2	*Enhanced primary productivity*	Higher CO_2 concentrations benefit photosynthesis, resulting in higher productivity (Rosenzweig et al. 2014).
Elevated CO_2	*More efficient water use*	Plants in high-CO_2 environments have more efficient stomatal gas exchanges, which reduce transpiration and improve water retention (Deryng et al. 2016).
Elevated CO_2	*Reduction in nutrition content*	Yield from crops in CO_2-rich conditions contains a lower percentage of key nutrients including protein, iron, and zinc (Müller et al. 2014; Myers et al. 2014; Medek et al. 2017).
Decreased precipitation	*Increase in water stress and mortality*	Excessive transpiration demand causes plants to reduce gas exchanges for photosynthesis, conserving water at the expense of primary production. Plant water loss can lead to wilting and mortality.
Increased precipitation	*Reduction in water stress*	Areas that regularly experience drought conditions likely stand to benefit should mean precipitation increase.
More severe storms	*Plant damage*	High winds and hail can knock down, break, or uproot crops, leading to potentially severe losses.

Increase in extreme weather events

As the ISPC book states, food systems face increasing risks owing to progressive climate change now manifesting itself as more frequent, severe extreme weather events – heat waves, droughts, and floods (IPCC 2013). Often without warning, weather-related shocks can have catastrophic and reverberating impacts on the increasingly exposed global food system – through production, processing, distribution, retail, disposal, and waste. Simultaneously, malnutrition and ill health are arising from lack of access to nutritious food, exacerbated in crises such as food price spikes or shortages. For some countries, particularly import-dependent low-income countries, weather shocks and price spikes can lead to social unrest, famine, and migration. As the ISPC book states, the IPCC recently undertook a review of observed changes in extreme events (Seneviratne et al. 2012), and both models and observations provide more robust signals for temperature extremes (e.g., increases in warm days) than for hydrologic extremes (e.g., heavy precipitation events became more frequent in many regions even as other regions displayed the opposite trends) (Hartmann et al. 2013). Even in cases with clear increases in the frequency of extreme events, it may be difficult to determine whether this is a result of a shift in the overall distribution or an additional fundamental shift in the shape of the distribution (Hansen et al. 2012). There are no clear observational trends in major modes of climate variability such as the El Niño/Southern Oscillation, the North Atlantic Oscillation, or the Pacific Decadal Oscillation (Hartmann et al. 2013; ISPC 2018). Measures to deal with the impacts of extreme events as described in the analysed reports include early warning systems as well as disaster support systems that governments should develop to support endangered livelihoods.

In general, both the changes in physical climate variables and the increasing frequency of extreme events as described by the reports are seen as also impacting other biophysical systems, which in turn further affect agricultural systems (ISPC 2018). These impacts on other biophysical systems include sea-level rise, which potentially inundates low-lying areas; inland flooding; increased stress on water resources; and shifting climate zones, which affect agro-ecological zones and thus the threats of pests, diseases, and weeds. Climate change may also indirectly affect agriculture and food systems through economic and political disruption. Examples include a consistent and extended decline in sea ice that would allow for transportation of agricultural commodities through the Northwest Passage, more frequent disruption of major trading ports due to sea-level rise and more intense hurricanes, and the potential for social unrest and migration following extended agricultural droughts (ISPC 2018).

Various crop model simulations have been conducted to assess the impacts of the changes in biophysical variables on crops, particularly staple crops. The ISPC and the WRI report pessimistic yield changes at lower latitudes and in semi-arid regions where agriculture is already limited by high temperatures and water stress. Yield changes are more optimistic at high latitudes where cold temperatures are most limiting, although the potential for poleward expansion is hindered by shallow soils with poor drainage as well as vast forests that are important in efforts to mitigate climate change risk. Direct climate impacts are also expected to affect aquaculture, wild fisheries, and livestock. The WRI furthermore points to the fear that the worst consequences of climate change are likely to be felt in sub-Saharan Africa and South Asia, the two most food-insecure regions of the world. Although not certain, the WRI also shows that there is a high risk that some of the drier arable lands in Africa will cross thresholds and become unsuitable for crop production owing to decreased rainfall and/or greater rainfall variability. All these impacts are seen in the analysed reports as leading to increased food prices by 2050, with estimated average price increases ranging from 3 percent to 84 percent compared with a world without climate change (WRI 2019).

All the reported potential impacts on agriculture due to climate change point to the need for adaptation measures as a key imperative for the food sector. The WRI report highlights, after a comprehensive assessment of crop models that assess the impact of climate change on various crops and the potential for adaptation responses, that there exists a significant capacity to adapt. But there is high uncertainty about the extent to which adaptation can offset the adverse effects of climate change, and it is doubtful that currently available forms of adaptation can fully offset these adverse effects.

Increase in GHG emission from the food sector

The WRI report, which did an extensive analysis of what it calls the GHG emissions gap, states that agriculture and associated land-use change such as deforestation accounted for nearly one quarter of global GHG emissions in 2010. Of these, agricultural production contributed more than half. The WRI estimates that agricultural emissions (mainly from livestock production, fertilizer use, and rice production) are projected to grow by at least 28 percent between 2010 and 2050, which will present a significant barrier to reaching the Paris Agreement targets. Based on a target of around 21 gigatons (Gt) of carbon dioxide equivalent (CO_2e) per year to achieve the Paris Agreement goals and using the annual production emissions and annualized emissions from land-use change in its business-as-usual baseline projection, the WRI estimates that agriculture would generate about 70 percent of allowable emissions from all human sources, leaving little room for emissions from non-agricultural sectors. Under an alternative baseline, agriculture would generate more than 80 percent of allowable emissions. The FOLU report points particularly to the threatening effects of methane emissions from livestock and rice production, stating that agriculture accounts for 50 percent of anthropogenic methane emissions. As methane's per tonne potential impact on global warming in the next few decades will be far more powerful than the likely impact of carbon dioxide, the reduction of methane emissions is an urgent priority to minimise the risk of overshooting temperature targets in the short-term and immediate future. Options to reduce GHG emissions from the food sector are mentioned by almost all reports and are wide ranging, including supply-side measures, such as changing feedstocks for ruminants and new rice and manure management systems; fossil fuel–free innovations across the whole sector; better land use management such as for peatlands; and reductions in demand for products with high GHG emission profiles. The RethinkX report sees large potential for precision fermentation to revolutionize the production of proteins, greatly reducing the need for raising livestock and potentially leading to the collapse of the whole industry within less than 10 years.

3.2 Environmental issues

The environment and the food system have a two-way relationship which produces various outcomes. A healthy environment supports the food system by providing a wide range of inputs, and a degraded environment limits the food system. Similarly, sustainable food systems can work to improve or degrade the environment. In this section we discuss what the reports highlight in terms of the food system impacts of water pollution and scarcity, biodiversity loss, soil and land resources, and emerging drivers such as aquaculture (**table 4)**.

Water scarcity and pollution

Water scarcity will continue to be a problem. According to some estimates, half of the world's population will live in water-stressed areas by 2050 (FOLU 2019). Because the demand for food and crop cultivation will continue to increase owing to population increase and diet changes, this water scarcity poses a big threat to the food system. Demand for water will also come from other sectors such as industry and municipal use, which are projected to increase demand by 200 percent in 2050, putting further strain on the available water resources (Strzepek and Boehlert 2010). Another driver of water scarcity is climate change, which affects the spatial and temporal distribution of precipitation, further reducing the supply of available water in particular areas.

The reports suggest addressing this challenge by improving water use efficiency and reducing water demand. WEF, for example, identifies four areas of potential freshwater withdrawal savings: introduce alternative proteins and save 400 billion cubic metres of water (they estimate that if 10–15 percent of global animal protein consumption were replaced with alternative proteins by 2030, we could see CO_2e emissions reduced by 550–950 megatons); promote value chain linkages using mobile service technology and reduce freshwater withdrawal by 100 billion cubic metres; use precision agriculture for input and water management and reduce water withdrawal by 180 billion cubic metres; and finally, use off-grid renewable energy and storage to save 250 billion in freshwater withdrawals. The NAP advocates for reduction of water use by using water-saving technologies, increasing productivity through controlled environments, and using alternative sources of water. Others suggest growing different crops – the GKI identifies millet as a crop that has been grown in Africa and Asia, has low water use, and is more drought resistant than other grains. The ISPC highlights that land grabbing is an extension of countries resolving their water scarcity issues by importing water virtually through traded goods (ISPC 2018). Water availability is compounded by water pollution, which further reduces the 'usable' water available. This pollution is driven by application of fertiliser and other agrochemicals, which is expected to increase as demand for food increases now and in the future.

Nutrient scarcity

By some estimates, the world has exceeded the planetary boundary for nitrogen (Steffen et al. 2015). The planetary boundary is intended as a guardrail within which resource use must occur and beyond which feedback for that resource's use may result in undesired consequences. Even so, the ISPC estimates that nutrient demand will double by 2050, and FOLU asserts that nitrogen-use efficiency varies widely by region and crop, but it rarely exceeds 60 percent, even in well-managed systems. Similarly, the global food system is dependent on phosphorus, sourced primarily from phosphate rock–based mineral fertilisers, which are finite. On the one hand, therefore, scarcity of nutrients will become a major problem for the food system. According to the FOLU report, only 15–20 percent of nitrogen and phosphorus applied to crops reach consumers, and a miniscule 2 percent in cities is looped back into the food production system. One of the main impacts of phosphorus scarcity, for example, would be to prevent agricultural intensification by limiting the production of resource-intensive crops (Neset and Cordell 2012). The scarcity will particularly impact the ability to close yield gaps and food gaps, further harming areas that currently face production limitations due to lack of nutrients that have significant impacts on yields (Mueller et al. 2012). On the other hand, increasing application of these nutrients will continue to impact waterways, affecting a suite of outcomes, including the agri-food sector itself, as well as other activities dependent on water quality (Keeler et al. 2012).

Table 4. Environmental drivers of food system change, their trends, and associated pathways for food system change

Food system drivers	Current trends in drivers	WEF	GAIN	NAP	HLPE	WRI	GKI	FOLU	ISPC	WIPO	RethinkX	Proposed pathways for food system change	WEF	GAIN	NAP	HLPE	WRI	GKI	FOLU	ISPC	WIPO	RethinkX
Environmental issues	Water pollution			●	●			●	●			Manure management					●					
												Innovative fertilizer					●					
	Water scarcity	●		●	●	●			●			Improved water management					●					
	Nutrient scarcity	●		●	●				●													
	Land use competition				●	●		●	●			Phasing out of bioenergy					●		●			
	(e.g., conservation, urban sprawl)											Protection of natural landscapes					●		●			
												Designation of efficient agricultural zones					●					
	Land grabbing					●	●	●	●													
	Biodiversity loss *(agro- and wild)*	●		●	●	●		●	●		●	Identification of marginal agricultural lands for reforestation					●					
												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							●			
	Invasive species			●					●													
	Soil degradation	●		●	●	●	●	●	●			R&D in soil and water management	●	●	●		●	●			●	
												Incentives for regenerative agriculture					●		●			
												Reforms in natural resource governance and tenure					●					
	Overfishing					●		●	●			Increase in sustainable aquaculture production							●			
												Limits on fish catch to reproduction levels					●		●			
												Removal of harmful subsidies							●			
												Protection of marine grounds/waters/areas							●			
	Aquaculture growth	●		●		●		●	●		●	Policy options to influence sustainable intensification					●		●			
												Investment in technological innovation and transfer					●		●			
												Spatial planning of aquaculture and feed production		●			●					●

Land use competition

Globally agriculture remains the dominant land use – over a third of terrestrial land surface is now under agricultural cultivation or used for animal husbandry (Foley et al. 2011). Based on current undernourishment trends and expected future demand, various studies foresee possible expansion of agricultural land. At the same time, studies also foresee the competition for land to intensify though to varying degrees (HLPE 2020; FOLU 2019; ISPC 2018). There are, however, several threats to both the potential expansion of agriculture for food and competition over its current land use. First, strategies to reduce greenhouse gas emissions using biofuels from plantations require land. These plantations can be developed on abandoned agricultural lands or can operate in direct competition with the food system by taking food crops (such as corn/maize) and converting them into fuel. The impacts on the food system therefore include reduced land available for food production and the removal of food products from the food supply. Cultivation of other non-food crops, such as rubber, that fetch a higher market price also threatens food production.

The reports propose solutions which might reduce the impacts of this land competition. For example, the expected reduction in livestock production (which is the biggest contributor of food emissions), driven by alternative protein options highlighted by various studies, could signal reduced land demand as livestock production declines. The RethinkX report expects livestock production to decrease by 60 percent in 2030 as precision fermentation of proteins replaces animal-source proteins. This pathway would reduce land use competition, at least between livestock production and other uses of land (and may even make it available for biodiversity conservation). It would also lower emissions from food, thereby potentially reducing the demand for land-based emissions mitigation – and thus reducing the efforts of these efforts on the food system. The HPLE expects biofuels of the future, another competitor for land, to be more focused on advanced technologies and less on tree planting, an approach which will also reduce land use competition.

Land grabbing

Large-scale land acquisition, mainly by international purchasers and local wealthy buyers, appears to have increased in recent years (WRI 2019). According to the WRI report, the majority of the land grabs occurred in Africa and Asia and tend to affect rural populations. Here agribusinesses acquire land and consolidate their holdings, often illegally, and displace communities dependent on these lands. These actions have some implications for the food system. First, in most of Africa and Asia, small-scale and smallholder farmers contribute significantly to food production (Ricciardi et al. 2018), and displacing them directly affects food availability in these places. Land acquisitions by foreign investors are not always aligned with local priorities, and large multinational corporations can use land for non-food purposes. For example, a 2019 study showed that most of the large-scale land purchases (over 200 ha) were used for speculative purposes and were not necessarily intended to be used for agriculture (Agrawal et al. 2019).

For this reason, the FOLU report suggests establishing full transparency and banning exploitation in supply chains. The WRI highlights the biological impacts of land grabs, which have so far been assessed predominantly in terms of social outcomes. The ISPC, on the other hand, as highlighted in the water scarcity section, sees this trend as an extension of countries' gaining access to more water. These large land acquisitions are in line with some of the scenarios discussed in the reports (e.g., the Survival of the Richest Scenario describes a future in which wealthy populations are able to produce and innovate to meet their needs; isolated, poor, or import-dependent markets face intensifying hunger and poverty; WEF 2017).

Biodiversity loss

In the analysed reports biodiversity loss is expected to continue into the future. For example, even in the best-case scenario described in the FOLU report, called Better Future, the biodiversity intactness index (BII, which is an indicator of the average abundance of a large and diverse set of organisms in a given geographical area; Scholes and Biggs 2005) is expected to marginally decrease. This is driven primarily by expansion in agricultural land to increase food production, but also increasing land grabs used to grow plantations. The loss of biodiversity has several implications and impacts for the agri-food system. The HPLE, through reference to an FAO report, highlights that 75 percent of the world's crop diversity was lost between 1900 and 2000, with rapid acceleration happening after 1950. Crop and animal diversity are dependent on general biodiversity, and declines in biodiversity will negatively affect this diversity. With the advent of new biotechnologies and precision gene editing, genetic material from wild species (wild biodiversity) has the potential to unlock future foods and nutrition. The continued loss of biodiversity, as described in several reports and assessments (e.g., IPBES 2019), severely reduces this potential.

The agri-food system also contributes to fragmenting land, which leads to further biodiversity loss by disrupting important species corridors. Biodiversity underpins ecosystem services provision (Mace et al. 2012), and several of these ecosystem services are important inputs into the agricultural food production system. By contributing to biodiversity loss, the agri-food system is eating into its own future inputs, such as water quality, water quantity, and gene pool. Solutions suggested by various reports include the reduction of meat consumption and livestock production as an opportunity for restoration and conservation. The RethinkX report paints a future where land used for livestock will go down by 60 percent by 2030, and this land can be used to conserve biodiversity. The HPLE highlights the problems associated with biodiversity loss by focusing on crop diversity loss. This echoes similar sentiments expressed by the IPBES, which in its most recent global assessment found declining biodiversity linked to agricultural expansion and showed how these declines in turn affect agricultural productivity.

Soil degradation

Soil degradation is expected to worsen in the coming decades. Like most drivers, soil degradation has a complicated relationship with the agri-food system. First, degraded soils contribute to declining yields. Declining yields in turn lead to overapplication of fertilisers, which further degrade the land. Soil degradation is therefore influenced by a number of factors, including poor land management and overapplication of nutrients. Besides the 'local' drivers of soil degradation as described, demand for agricultural products from faraway places, facilitated through agricultural trade, is also seen as a driver of soil degradation. There is now increasing evidence that 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 (Wilting et al. 2017; Lenzen et al. 2012). The mechanism by which these distant places are linked is increasingly referred to as telecoupling (Liu et al. 2018). Some reports, such as GAIN and GKI, highlight innovations that could help monitor and improve soil health, such as regenerative agricultural practices and the reform of natural resource governance systems (WRI 2019; FOLU 2019).

Overfishing and Aquaculture
Much of the world's fisheries are overfished, and this will continue to increase into the future. At the same time, wild catch fisheries have stagnated (i.e., wild catch is no longer sufficient to feed the growing demand for fish [WRI 2019; FOLU 2019; GKI 2017] at a time when the demand for fish proteins are high). Fish still remains an important source of micronutrients worldwide (Hicks et al. 2019). Aquaculture has grown rapidly in the last number of years as a complementary source of fish protein. The ISPC reports that aquaculture increased substantially and has exceeded wild-caught products for human consumption since 2014 (ISPC 2019). Given that wild-caught fishing has stagnated and overfishing is still increasing, aquaculture will become an important source of fisheries to meet the growing demand in the future (WRI 2019). As a result, the FOLU report emphasizes the need for investment in aquaculture. The impacts of aquaculture on the food system are so far missed. On the one hand, aquaculture fills a real need for non-livestock proteins at a time when wild-caught fisheries are overfished. Additionally, aquaculture will help supply the important micronutrients which people lack in many parts of the world. On the other hand, the constraints of aquaculture driven by feed availability (FOLU 2019) post a threat to the food system. Aquaculture has been shown to compete for land with agriculture by using land to grow feed or by using food to feed fish.

Potential solutions put forward to address this challenge of feed include insect-based feed and other alternative fish feeds (FOLU 2019; GAIN 2019; ISPC 2018). Overall, aquaculture looks to be a significant driver of resource use (including land for growing feed and water). So far, estimates show aquaculture using fewer resources than livestock in 2050, although the impacts are uncertain and potentially large (Froehlich et al. 2018).

3.3 Societal changes

Social drivers are considered key to food systems, partly because food systems cater primarily to human nutritional status, well-being, and livelihoods. This importance is reflected across reports, as many highlight that the ability to ignite food system change relies strongly on extent to which we can achieve dietary change, meet food demand, achieve equitable outcomes, and manage demographics along with the related spatial distribution of people and activities. These elements are considered key points in effecting change, albeit with different *mechanisms of change*. In the following section we briefly outline why these elements are considered crucial and how the various reports foresee their mechanisms of change (**table 5**).

Dietary change
The sustainability of our diet, environmentally and socially, is a major concern: our average global dietary profile has a large ecological footprint and is unhealthy and unbalanced. Multiple reports flag dietary change as a key driver of future food systems, emphasising the trend towards an increase in obesity and undernourishment through an average dietary pattern that is a strong driver of GHG emission and natural resource degradation (FOLU 2019; WEF 2018; ISPC 2018). A range of different approaches to address dietary change are suggested, hinging on policy actions and technological innovation. FOLU and WRI mention the role of policy in steering dietary change to a wanted direction. This could, for example, be a tax on unsustainable foods (e.g., a sugar tax) or regulations that underscore sustainability across the supply chain. FOLU takes this a step further by suggesting public procurement to increase sustainable food demand and public financial support for small and medium

enterprises that deal with health and sustainable foods. Other pathways of change lean on technological innovation. WEF sees a future where personalised nutrition and nutrigenetics can improve dietary patterns and significantly reduce obesity. Lastly, many reports mention alternative protein sources for sustainable and healthy diets. Advancements in alternative proteins and increases in the products on offer are needed to help the consumer demand for these products grow further.

Growing inequalities

An influential driver of societal changes in food systems consists of growing inequalities. WRI, FOLU, and ISPC stress the lack of food security for the majority of the world's population, a condition that strongly influences their health status and behaviour in food systems. Here, improved access to food system resources is stressed as a pathway to redirect these drivers. This pathway manifests partly through access to food production technologies and partly through ensuring education and health care. For example, many reports in this synthesis point to the need for scalable and affordable innovations for food production, processing, and retail. GKI also sees potential for various shared food-processing approaches to address problems of access: for example, shared food-packaging facilities and modular processing facilities, each preferably fuelled by renewable energy. Such innovations would also contribute to the ability of small-scale farmers and entrepreneurs to increase their share of final product value. FOLU stresses the need for extra legislation to increase farmers' income in relation to final product value. The position of women and the securing of their rights are also often mentioned. Nevertheless, while women's position is considered by many to be an essential driver of the food system, only FOLU outlines a concrete pathway focussing on ensuring the rights and well-being of women and girls.

Growing food demand

Many of the exercises look at food in the context of a growing world population, citing consequent growing food demand as crucial driver of food system change. The global population is estimated to reach 9 billion, and perhaps even more, by 2050 (WRI 2019). The challenge of feeding this growing population in a sustainable manner is what instigated many of these foresight exercises in the first place. Curbing the demand for food is also seen as a key lever to reaching these goals. Pathways highlighted to do so are more technological and focus on further reducing food waste and losses and increasing crop yields and livestock efficiency. Both measures increase the efficiency of the food system even further and can thereby influence total food demand.

Changing food culture and knowledge

A number of reports focus on changing food cultures and food knowledge. The popularity of ready-to-eat food is increasing globally, thanks to digital services, home delivery of foods, and ready-to-eat offerings in supermarkets: all change the culture around food, especially in urban areas. Digital accessibility of food knowledge also shapes public knowledge of food, perhaps making it even more diverse. ISPC emphasises that traditional ways of communicating food knowledge are becoming less appropriate and demands new ways to educate about food. WRI and FOLU see a specific role for industry actors to take the lead in producing healthier and more sustainable foods, as well as in using effective marketing to increase consumption of these products. WRI emphasises that the impact of more traditional public campaigns is limited compared with the potential of marketing sustainable foods.

Table 5. Societal drivers of food system change, their trends, and associated pathways for food system change

Food system drivers	Current trends in drivers	WEF	GAIN	NAP	HLPE	WRI	GKI	FOLU	ISPC	WIPO	RethinkX	Proposed pathways for food system change	WEF	GAIN	NAP	HLPE	WRI	GKI	FOLU	ISPC	WIPO	RethinkX
Societal changes	Dietary change	●				●		●	●			Policy options to influence diets					●		●			
												Financing for SMEs offering healthy and sustainable food							●			
												Public procurement of heathy and sustainable food							●			
												Personalized nutrition	●									
												Influence on purchasing decisions					●					
												Increased offerings of alternative proteins	●				●		●			
	Growing inequalities					●		●	●			Access to food system resources					●	●	●			
												Shared food-processing facilities						●				
												Policy to increase farmer's share of final product value							●			
												Protection of rights and well-being of women and girls							●			
	Growing food demand					●		●	●			Reduction in food loss and waste					●		●			
												Increased livestock efficiency					●					
												Increased crop yields					●		●			
	Changing food culture and knowledge					●			●		●	Engagement with food industry for health and sustainability					●		●			
												Effective marketing of healthy and sustainable foods					●		●			
	Increasing demographic imbalances								●			Improved women's education					●		●			
												Improve dreproductive health care					●		●			
	Growing urbanization					●		●	●			Zoning to limit competition from urban encroachment							●			
	Increasing migration								●													

Increasing demographic imbalances

Besides the issue of a growing world population, ISPC emphasises how the increasingly unbalanced global population is driving food systems change. They highlight future trends pointing to an aging Global North, while Africa will have a higher proportion of adolescents. These dynamics bring different challenges connected to public health and diet. Few options to address these imbalances are offered, apart from improving women's education and access to reproductive health care to overall flatten the curve of population growth.

Growing urbanization

The majority of the growing world population is expected to reside in urban areas, underscoring growing urbanisation as a key driver in the overall land-use dilemma. Urban areas are a major consumer and put large demands on food systems, along with specific and sophisticated infrastructures. WRI, FOLU, and ISPC highlight urbanisation as a key driver in light of the other demands on land use. FOLU proposes zoning and spatial planning to limit competition from urban encroachment.

3.4 Market dynamics

The global orientation of food systems is mostly market driven, highlighting the historical major role of the market in shaping food systems. In terms of future dynamics, the reports focus mostly on the potential of the market to become a vehicle for sustainability. Emphasised here are trends towards fair commerce, sustainable innovations, and finance to drive food systems in the future. Lastly, the growing influence of emerging economies is underscored as influential to food systems (**table 6**).

Market-designed innovation

The industry's role in pushing innovation for food systems change is emphasised in several reports. RethinkX and FOLU specifically focus on the business opportunities that lie in innovation. Reasoning that industry can afford to take more risks and be more experimental, they see industry as an important actor in pushing innovations further. This ranges from alternative protein development that is scalable to Internet of Things–type supply-chain innovations. Notably, cost-effectiveness remains a priority in most of the market-designed innovation. WRI emphasises the necessity for accessible and sustainable innovations.

Fair food commerce

The possibility of making a decent living by producing food relies strongly on the fairness of commerce. The lack of fair commerce is cited by WRI and FOLU as a driver of future food system change. To address these issues, FOLU proposes more transparency in food supply chains and management of food prices to ensure fair prices.

Finance for green technologies

Reports cite the level of finance for green technologies as a driver, reasoning again that market actors and financers can take more risks when investing in technologies and innovation processes (GKI 2017; FOLU 2019). Specific attention is paid to directing such investments to climate-smart technologies that are able to deal with future biophysical changes (WRI 2019; GKI 2017; FOLU 2019) and close-

Table 6. Market dynamics as drivers of food system change, their trends, and associated pathways for food system change

Food system drivers	Current trends in drivers	WEF	GAIN	NAP	HLPE	WRI	GKI	FOLU	ISPC	WIPO	RethinkX	Proposed pathways for food system change	WEF	GAIN	NAP	HLPE	WRI	GKI	FOLU	ISPC	WIPO	RethinkX
Market dynamics	Market-designed innovation							●				Accessible and sustainable innovations					●			●		●
	Fair food commerce					●		●				Managed food prices							●			
												Transparency in the food supply chain							●			
	Finance for green technologies						●	●				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								●													

the-loop technologies that help reduce food loss and waste and better cycle nutrients (GKI 2017; FOLU 2019). Moreover, FOLU proposes that corporations show ambition and set targets for food loss and waste reduction. Moving to more green industries also means that less sustainable activities will need to be phased out, and FOLU emphasises the need to support workers become displaced in phased-out industries. This support could be in the form of re-education or financial assistance.

3.5 Governance dynamics

Governance is an important driver in the food system. It can moderate unwanted trends and incentivize desired dynamics to reach more sustainable food systems. Reports in this study focus on governance as a way to regulate and give more equitable structure to the system. The key governance drivers for food systems are outlined in **table 7** and discussed in this section.

Food system regulations

Regulation is an essential part of food systems' structure. It outlines the boundaries within which food system activities can take place and has a lot of influence on the sustainability of the system. Throughout the reports the weight of this driver is shown in the extent to which pathways of change feature regulatory measures as a solution. There are two major ways to regulate food systems: through taxes and through policy incentives. These options underlie strategies for change in the FOLU and WRI reports. Taxes for a sustainable food system could, for example, take the form of a tax on high-sugar-content food commodities. Through higher pricing of certain unhealthy or unsustainable products, consumers are discouraged from buying these products. One could also take the route of incentivizing sustainable food by, for example, providing subsidies for sustainable practices or giving financial benefits to actors who choose sustainable supply-chain options. Another role of governance is to facilitate an enabling environment. The WEF reports emphasize the role of public and private sector investments to facilitate the development and adoption of innovations in the food system. Because of the complexity of the food system and its many interlinked components (**figure 1**), governance systems can either break or make these systems.

Land tenure

Certainty of land tenure is an important driver of sustainable land practices. Farmers who have secure land tenure are more likely to think about the longer-term effects of their farming practices on natural resources. This security is increasingly threated by various mega developments (Laurence et al. 2015). FOLU stresses the need for young farmers to have security and stability in their livelihoods through land rights. WRI and FOLU suggest that granting tenure to land should be linked with sustainable practices. In essence, a prospective land user needs to prove their sustainable management of the land to be granted tenure and must continue to do so to keep tenure. WEF suggests using blockchain, a type of distributed ledger technology, to reduce transaction costs and cut the time needed to process payments and track land tenure. It underscores the need to reflect on land tenure regulations for different scales of land use, as corporate use and smallholder use of land require different steering actions.

Table 7. Governance dynamics as drivers of food system change, their trends, and associated pathways for food system change

Food system drivers	Current trends in drivers	WEF	GAIN	NAP	HLPE	WRI	GKI	FOLU	ISPC	WIPO	RethinkX	Proposed pathways for food system change	WEF	GAIN	NAP	HLPE	WRI	GKI	FOLU	ISPC	WIPO	RethinkX
Governance dynamics	Food system regulations					●		●				Taxes for sustainability					●		●			
												Policy incentives for sustainability					●		●	●		
	Land tenure					●		●				Restrictions on unsustainable land use					●		●			
												Support for young entrepreneurs' access to land							●			
	Role of international organisations					●		●	●			R&D of accessible adaptive technologies					●		●	●		
												Protection of common pool resources							●			
	Protected areas					●		●				Allocation of protected areas					●		●			
												Investment in common pool resources							●			
	Multi-actor governance models							●	●			Increased global coordination of actions					●		●			
												Civil society holding public and private actors accountable							●	●		
	Public good innovations	●						●				Affordable technologies targeted at the poor	●				●	●				
												Incentives for future innovation markets					●		●			
	Safety nets							●				Social welfare structures and risk management tools							●			
	Conflict impacts								●													

Role of the international organisations

International organisations are recognised to have a key role in contributing to the provision of general and public support to steer food systems towards sustainability. The WEF report highlights several stakeholders, including international organizations, that have a role in effectively providing infrastructure, facilitating policy and regulations, and investing in scale innovations. One worrying trend in this regard is the reduced funding for international organisations. WRI, for example, emphasises the reduction of CGIAR funds over the years, which they suggest is undercutting vital R&D for adaptive farming technologies and breeding research. WRI and FOLU both see a critical role for international organisations in leading R&D on accessible and adaptive technologies for sustainable food systems. FOLU also highlights international organisations' ability to protect common pool resources, whereas the regulatory boundaries of nation-states might restrict them. WEF suggests that these organizations can also help address the crucial capacity-building challenges that many technology innovators face.

Protected areas

Protection of natural landscapes is considered primarily an aspect of governance. The allocation of areas that need protection for the common good is generally trusted to global or national governance dynamics. This driver is considered key in relation to the dire state of natural resources. FOLU and WRI emphasise the need for governance actors to take the lead in protecting common good natural resources as a pathway to ecological sustainability.

Multi-actor governance models

The food system connects various actors on multiple levels. For example, a soy farmer in Brazil is connected to Chinese consumers through demand for animal protein. Similarly, farmers in various parts of the world are linked to one another through global markets and affected by national-level policy decisions such as subsidies. There are sectoral connections too – many agricultural subsidies promote high-emission cattle production and pollution from fertilizer overuse. The reports emphasise that effectively managing these connections requires coordination and collaboration between various types and scales of actors. For example, the WEF report asserts that the private sector, public sector, international organisations, non-profits, and donor and investment funds need to make a concerted effort to scale innovative technologies with the potential to have a positive impact on food systems. A key example is the necessity to coordinate action in the mitigation of climate change. This not only requires all countries worldwide to put changes and measures into place, but also requires decisive action from corporate actors and civil society. The ability to come to well-functioning multi-actor governance models is therefore considered a *must* in all reports. In fact, this is often embedded as an assumption, because without it none of the global targets or food system outcomes will be met. To strengthen these processes and secure their success, FOLU proposes that civil society act as the third party that holds public and private actors accountable for their actions.

Public good innovations

Another driver of future food systems will be the extent to which public good innovations can be developed – as opposed to market-designed innovations primarily oriented at cost-efficiency. The NAP report shows that government investments in agricultural research and development have been declining, a trend that is likely to be reflected in other countries. As investments and innovations are increasingly spearheaded by the private sector, their affordability and accessibility will be limited to those with the means or those within reach of the market. The accessibility of crucial technologies to the poor will be a key lever in reaching a future food system that is equitable, particularly for smallholder farmers, who not only provide a substantial share of food for the world (Ricciardi et al. 2018) but are also vulnerable to the well-documented challenges of market, credit, and insurance access. The WRI, GKI, and WEF highlight a range of innovative solutions to many of the problems in the food system and stress the need for public good innovations to be targeted to the poor. WRI and FOLU also underscore the ability of public actors to incentivise future innovation markets by, for example, lowering taxes or providing subsidies for innovations in a given domain.

Safety nets
Any dynamics of change result in winners and losers. For example, decisions to phase out certain unsustainable industries affect employees of those industries and put their livelihoods at risk. There need to be support systems for the people that are on the 'losing' side of change. FOLU proposes mechanisms to address this issue by setting up social welfare structures and providing risk management tools. These could consist of income support or re-education pathways to jobs in sustainable and growing industries. The elements of the scenarios described in the reports, most of which have alternative future pathways in which there will be substantial gaps between those benefitting and those losing, are in fact here today. WEF reports that in 2016 the richest 20 percent of the world's population consumed 86 percent of the world's resources. In the same year, the percentage of the population that is undernourished spent 60–80 percent of their income on food.

3.6 Technological developments

Technological developments feature strongly as drivers of food systems. Technological development led to the start of the Green Revolution, which was a major influence on the shaping of the global food economy. Today there is still strong belief in the ability of technology to offer solutions to some of the world's complex challenges. There is now talk of a Fourth Industrial Revolution, which is driven by digital building blocks (e.g., artificial intelligence and machine learning), advances in science (e.g., next-generation biotechnologies), and advanced manufacturing (e.g., autonomous vehicles and nanotechnologies). These are playing a disruptive and innovative role in the food system. Food foresight reports see the progress made in technology as key to the future of food systems. This factor can be divided into several layered trends that we set out in **table 8** and discuss in detail in this chapter.

Advances in conventional breeding techniques and new biotechnology techniques
Improving the desirability of seeds, crops, animals, and other food products has been done since the domestication of wild crops 10,000 years ago. The techniques used, however, have changed radically. For example, historically there were three ways to improve seeds: open pollination, hybridity, and genetic modification. In many ways, these are still important. The WRI advocates for crop yield improvements through improved breeding, and WEF calls for improving precision agriculture for input and water use optimization. Advances in science, such as next-generation biotechnologies and genomics, and new energy technologies are bringing significant changes to the food system. Gene editing, for example, offers the opportunity for substantial improvements in yields and environmental

Table 8.Technological drivers of food system change, their trends, and associated pathways for food system change

Food system drivers	Current trends in drivers	WEF	GAIN	NAP	HLPE	WRI	GKI	FOLU	ISPC	WIPO	RethinkX	Proposed pathways for food system change	WEF	GAIN	NAP	HLPE	WRI	GKI	FOLU	ISPC	WIPO	RethinkX
Technological developments	New biotechnology techniques	●				●	●	●	●	●		Open access/sharing of genomic advances	●				●				●	
	Advances in conventional breeding techniques					●						Sharing of breeding advances					●			●	●	
	Advances in land management Techniques					●		●				Increase in R&D for regenerative agriculture					●		●			
												Increase in communication and outreach					●	●	●			
	Targeted innovation					●	●					Social innovations in low-tech environments						●				
												Flexible regulation to incentivise targeted innovation					●					
	Renewable energy innovations	●				●	●	●				Scale up renewal energy and make it broadly accessible	●				●	●	●			
	Convergence of information and biotechnology	●				●		●	●		●	Precision fermentation to engineer proteins	●									●
	Big Data and AI for food	●					●	●	●			Precision agriculture					●			●		
												Open access to public sector data							●			
												Expansion of mobile service delivery for farmers	●				●		●			
												Insurance for farmers						●				
	Internet of Things	●					●		●			Virtual farm-to-fork marketplace						●				
												Real-time supply-chain for transparency & traceability	●							●		

and nutritional outcomes. According to the NAP report, gene editing is aided by recent advances in genomics, transcriptomics, proteomics, and metabolomics, and it has the potential to accelerate breeding to generate traits in plants that improve efficiency, resilience, and sustainability. The ISPC shows that biotechnology already makes a significant contribution to crop and animal improvement, and this is expected to accelerate in the future. Similarly, more advanced technologies such as CRISPR technology could provide a way to achieve multi-trait improvements. The newer technologies are currently constrained by costs, regulatory frameworks (in some cases due to ethics), and access.

Convergence of information and biotechnology

The reports highlight that the advances in biotechnology coincide with major advances in data technology. On the one hand, the current era is characterised by biotechnological advancements described above, and on the other hand is often characterised as the age of big data, and There are now several technological developments geared specifically towards helping to process and make sense of this data. Machine learning, for example, is used to recognise patterns, which can be helpful given the scale and frequency of changes in climate, markets, political conditions, and other drivers affecting the food system. Being smart about data can improve supply chains, reduce waste, connect farmers to markets, and facilitate targeted nutrigenomics for personalised nutrition. Combining these advances can provide a powerful tool. According to the WEF report, advanced precision agriculture technologies in combination with machine learning, big data analytics, and advanced robotics could allow farmers to apply the optimal amount of inputs for each crop and assist with the management of livestock and aquaculture, thereby boosting yields and reducing water use and greenhouse gas emissions.

Advances in land management techniques

Progress towards sustainable land management is considered crucial in driving future food systems. Given that a large portion of the global farming population consists of smallholder farmers who are unable to make large investments in the infrastructure needed for advanced technologies, developments in land management are still crucial. Here, FOLU and WRI see possibilities in regenerative agriculture, such as agro-ecology and agro-forestry. The underlying idea is that these land management techniques approach farming in a more circular manner and are even able to restore soil and water quality when they have been degraded by unsustainable practices. They underline that regenerative agriculture requires new knowledge and a shift in practices but is possible with limited investments and can therefore be made accessible and scalable. Communication and outreach about good practices in land management remain crucial in sharing valuable knowledge and know-how about regenerative agriculture. GKI joins these two reports in stressing the need for increased sharing of knowledge, through amplification of the voices of champions, mobile educational centres, and use of digital communication technologies to improve farmers' communication for learning and information about land management.

Targeted innovation

Innovation has been emphasised as a driver a few times. Notable throughout the reports is the importance of more targeted innovation processes – in other words, innovation aimed at a more specific public good objective. The crucial point here is that such innovations are generally considered to be focussed on their sustainability contribution and less on cost-effectiveness. Trends indicate a move towards innovations that can be patented, and these are often difficult to access for most of the global population. Investments in the development of public good innovations are crucial drivers of sustainability. Many of the innovations that are outlined in the GKI report are low-cost innovations designed to be scalable and accessible. These innovations lean strongly on social innovation such as the sharing of food-processing or food-packaging facilities. These innovations rethink some of the social structures that give shape to technology that would otherwise be inaccessible. Furthermore, WRI highlights the need for more flexible regulation to incentivise targeted innovation.

Renewable energy innovations

In bringing down the total levels of GHG emissions, much depends on technological developments in renewable energy innovation. Food systems are responsible for a large part of GHG emissions, and many argue this contribution can be brought down to net zero through the development of renewable energy innovations. WEF, GKI, FOLU, and WRI all point to the pressing need for accessible and scalable renewable energy innovations.

4. Scenario-based driver interactions & food system outcomes

4. Scenario-based driver interactions and food system outcomes

Forward-looking exercises are a useful tool for assessing the direction and impact of change. Through a futures lens it is possible to strategically think through the impact of interventions, based on a concrete systems understanding that is informed by scientific understanding and historical trends. This synthesis compares several key forward-looking exercises to assess the impacts of their proposed pathways of change. To get a comprehensive idea of how the proposed changes might affect the food system, this chapter focuses on the reports that present a systems understanding of change in food systems: the WRI and FOLU reports. We complement these with the WEF scenarios and two of the EAT-Lancet scenarios, as these are often embedded in other scenario exercises.

To compare these different exercises, we assess them based on their ability to deliver on three key food system outcomes (see **figure 1**): *food and nutrition security*, *environmental sustainability,* and *economic and social well-being.* **Table 10** captures the food systems impacts as described in these four reports. The weighting of the impact on food system outcomes is done by comparing them within the report only. Notably, the WRI, FOLU, and EAT scenarios use a baseline and show how a business-as-usual approach leads to bad performance across food system outcomes. They each offer approaches for dealing with these challenges and steering food system dynamics towards delivering on all food system outcomes. The WEF scenarios do not offer a baseline scenario and instead show how four radically different approaches will each shape the world, affecting food systems and their ability to deliver outcomes.

4.1 Scenario assumptions and system boundaries

To compare the food system outcomes of different scenario-based assessments, it is key to explore the embedded system boundaries and assumptions made about the functioning of the system. These elements are crucial to make sense of the data presented in a forward-looking exercise. In the following section we underline the assumptions and boundaries that were key to the scenario-based assessments and to operationalising the mechanisms of change in their proposed pathways.

4.1.1 World Resource Institute scenarios

The WRI report sets out a comprehensive scenario-based pathway for change towards more sustainable food systems. The impact of this pathway for change is modelled with the GlobAgri-WRR model, which relies strongly on FAO data. To highlight the extent of change that must be implemented compared with current practices, they set out the impacts of these pathways against the 2050 baseline scenario. Furthermore, based on expert judgment they show how a varying level of ambition in pursuing this pathway can make a difference in meeting the goal of sustainable food systems in 2050.

Baseline scenario

The business-as-usual, *baseline*, scenario already assumes significant progress in agricultural productivity compared with now. It entails agricultural productivity gains that close more than 80 percent of the land gap and roughly two-thirds of the GHG mitigation gap. Moreover, this scenario deviates from population growth estimates used in other reports, arguing that fertility rates have decreased less than expected, resulting in a global population of approximately 9.8 billion in 2050 based on the latest trends. Based on this scenario, they highlight the pressing challenges we face regarding a food gap, a land gap, and a GHG mitigation gap. It is unable to deliver all food systems goals sustainably.

Menu items performed in increasing levels of ambition

The report's authors outline an approach based on their assessment of the baseline scenario and the key drivers that shape it. To address the three major challenges that arise from the baseline scenario, they outline 12 menu items that address the key drivers for food system change.

Coordinated effort

The first scenario, *coordinated effort*, explores the impact of a global coordinated effort to perform these menu items. This scenario is characterised by limited economic costs, global coordination of policies (e.g., regarding allocation of productive agricultural lands), and global efforts to reduce meat consumption. Ultimately, this scenario is unable to address the food gap, land gap, and GHG mitigation gap; that is, it is unable to meet food demand without further increasing agricultural land expansion and GHG emissions. Compared with the baseline, this scenario makes only moderate progress towards meeting food system outcomes, falling short specifically in terms of environmental sustainability and equity.

Highly ambitious

The following scenario, *highly ambitious*, builds on the coordinated effort but is focused on 'technical achievability' and is 'less concerned with cost or practicability' (WRI 2019, p. 406). As the name signals, experts regard this overall as a feasible yet highly ambitious scenario. It builds on the development of measures, both governmental and technological, that can make a difference in addressing the gaps. At the bottom line, this scenario falls just shy of addressing the GHG mitigation gap but effectively increases food demand while decreasing total agricultural lands. Most food system outcomes are met in this scenario, which falls short on environmental sustainability.

Breakthrough technologies

Finally, the third scenario, *breakthrough technologies,* builds on the previous scenario and further factors in the impact of 'technological breakthroughs' that improve both performance and cost-effectiveness 'only in fields where science has shown significant progress' (WRI 2019, p. 406). This scenario can meet food demand, bring GHG emissions of food systems to net zero, and do so while drastically decreasing agricultural lands. As highlighted in the report, the feasibility of achieving all these breakthrough technologies is fragile as in many cases it depends on the level of investments made in R&D for technologies and global coordination. This scenario represents a future food system that delivers on all food system outcomes in a sustainable manner.

4.1.2 Food and Land Use Coalition scenarios

The report by FOLU sets out 'ten critical transitions' that together make up an integrated approach to transform food and land use systems towards social and ecological sustainability. The scenarios unpacked in the report are the result of connecting output from GLOBIOM, the World Bank Shockwave model, and separate diet and health modelling. To emphasise the impact of the proposed pathway to change, they compare its impacts against current trends.

Current trends

This baseline scenario, *Current trends*, aims to showcase the impact of a food systems future based on historical trends. This is achieved by leaning on the IPCC's Middle-of-the-Road scenario (SSP2), combined with climate assumptions of the Representative Concentration Pathway 6.0. This baseline scenario assumes moderate progress in, for example, yield growth and reduction of food loss and waste but a continuation of today's trends regarding food and nutrition security, biodiversity conservation, and trade. The report uses this baseline to calculate the social-ecological impact and the (hidden) costs connected to these challenges. This scenario is far from delivering the food system outcomes and represents something of a social and ecological doom scenario.

Better futures

The scenario *Better futures* shows the results of a series of policy recommendations that make up FOLU's proposed pathway of change. Here key assumptions about the impact of these policy recommendations are used as input for the model. These assumptions include, for example, a continued annual increase in agricultural productivity, ultimately leading to sufficient food production in 2030; a reduction in energy demand; and better governance and management of protected areas. As the report emphasises, key to realising this scenario is concrete action from 'national governments, business, financial sector, civil society, including academia and the international community' (FOLU 2019, p. 24). The impact of these recommendations is calculated in the social-ecological impact and financial impact. Above all the report stresses the economic price of the scenario by avoiding hidden costs and the amount of business opportunities embedded in these changes. The *Better futures* scenario can meet all food system outcomes sustainably.

4.1.3 EAT-Lancet Commission planetary health diet scenarios

Given the frequent use of the EAT-Lancet Commission's developed *planetary health diet* scenarios, a better understanding of their assumptions and boundaries is key to comprehending the exercises that use them. While this report does not take a full systems approach, the EAT-Lancet scenarios show the environmental impacts of several food system interventions that address diets, food waste, and food production. For this synthesis we have assessed the extremes of multiple scenarios from the EAT-Lancet report. Notably, these scenarios do not question global ability to meet total food demand: rather, they attempt to assess what actions related to dietary change, food waste, and food production would allow for social and ecological sustainability.

Business-as-usual + full waste

The baseline scenario used in the EAT-Lancet report is largely based on many of the SSP2 assumptions, the IPCC's Middle-of-the-Road scenario. This scenario entails increasing GHG emissions to produce food, increasing nitrogen and phosphorus application, and an 'absence of dedicated mitigation measures' (Willet et al. 2019, p. 471). It estimates that dietary changes will continue along existing trends, including a relatively high level of meat consumption for a large portion of the world population. As a result, meeting food demand would put ecological systems at serious risk and global temperatures would continue to rise. While this scenario can fulfil food demand, it is unable to meet food system outcomes sustainably.

PROD+ dietary shift + halve waste

The second EAT-Lancet scenario we highlight is their most ambitious one; it factors in production practices that can almost close yield gaps and can recycle nutrients at a much higher rate. Moreover, the scenario embeds mitigation options for food-related practices, resulting in net-zero-emission agriculture, halving of food loss and waste, and an optimisation of land use across regions which positively impacts biodiversity. This is partly achieved by the shift towards the *planetary health diet*, which is characterised by a high proportion of vegetables, whole grains, and plant-sourced protein and a major reduction in animal-source protein. This scenario also does not question the ability to meet global food demand; however, it does assess whether this dietary shift positively influences environmental impacts. While the report highlights that this scenario falls just short of fully meeting the outcome of environmental sustainability, the embedded interventions lead to a better delivery of all food system outcomes.

4.1.4 World Economic Forum scenarios

The WEF used a different approach to scenario development. The scenarios started by exploring two drivers of change that were seen as pivotal to shaping food systems over the next 20 to 30 years: the connectivity of markets and shifts in food demand between resource-intensive and resource-efficient consumption. This approach is more common in scenario planning than what the other exercises did and explores four plausible futures based on the key assumptions and additional driving forces conditioned by the two main drivers.

Survival of the richest

In this scenario, relatively few isolated, wealthy populations are able to produce and innovate to meet their needs; isolated, poor, or import-dependent markets face intensifying hunger and poverty. Most people are worse off, and climate change and environmental degradation continue to worsen. Food is not affordable to many, and there is widespread malnutrition and waste. They show the possibility of this scenario using current indicators: the richest 20 percent of the world's population consumes 86 percent of the world's resources; food-price volatility will likely disproportionately impact the urban poor, who already spend 60–80 percent of their income on food.

Unchecked consumption

In this scenario, there is accelerated trade driven by ever-increasing demand. Technology spurs efficiencies in food production and distribution, with yield improvements as the top priority, but the food is poor in quality, and health costs and obesity increase. Many global food producers and retailers benefit from an increase in sales due to higher demand for foods – especially multinational companies, which benefit from increased trade, globalization, and strong global brand recognition. This scenario is predicated on the Kuznets curve, based on the belief that society can grow now and fix environmental problems later. Current trends in non-communicable diseases and challenges with biodiversity loss and climate change point to early signs of this future.

Open-source sustainability
In this scenario, commodity markets have been stress-tested and checks and balances have been instated to reduce volatility and the risk of a crash. A stronger global economy enables more consumers to purchase food priced at its real cost, as influenced by new business models and policies that support sustainable choices and healthy diets. Not everyone wins in this scenario. Pricing food right increases the cost of food, and some farmers may be shut out of the new, more connected economy, without viable alternative livelihoods.

Local is the new global
In this scenario, there is a rise in local food movements as consumers increase their focus on sustainable local products and progressive policies successfully reduce the price point for healthier diets relative to unhealthy diets. Clear winners are the countries that can achieve self-reliance through available natural and human capital; import-dependent countries struggle to feed a growing population and face increasing malnutrition.

4.1.5 Shared Socioeconomic Pathways (SSPs) as used by the Climate Change community, IPFRI, and AgMIP

The Shared Socioeconomic Pathways (SSPs) are a set of scenarios developed for the use of the climate change modelling community. They were conceived by O'Neill et al. in 2015 and are linked to the so-called Representative Concentration Pathways (RCPs) that show four possible GHG emission pathways up to 2100. The SSPs have since then been used as the foundation of almost all forward-looking work around climate change questions, and their assumptions on GDP, population dynamics, and other variables are now also increasingly used by other communities, such as the food and agriculture one, for their forward-looking work.

Figure 4. Five Shared Socioeconomic Pathways (SSPs) representing different combinations of challenges to mitigation and to adaptation used by the climate change modelling community (O'Neill et al. 2015)

Although they don't portray food system changes, we included the SSPS in the synthesis work because they have been used by a number of the analysed reports. In addition, the SSPs have been used extensively by the Global Futures Program of IFPRI and its model IMPACT to look into the potential impacts of climate change on crops and livestock production in the developing world. The SSPs are also the foundation for the work of the AgMIP program (Agricultural Model Intercomparison and Improvement Program), which compares the results of various crop models based on different climate projections. The SSPs are a built around the key challenge for the climate change community portraying different combinations of socio-economic challenges around adaptation and GHG mitigation (see **figure 4**).

4.2 Food system outcomes

This section analyses the status of food system outcomes as embedded in the scenario reports (**table 10**). It compares the differences in pathways across the scenario reports to better understand the impact of different pathways of change.

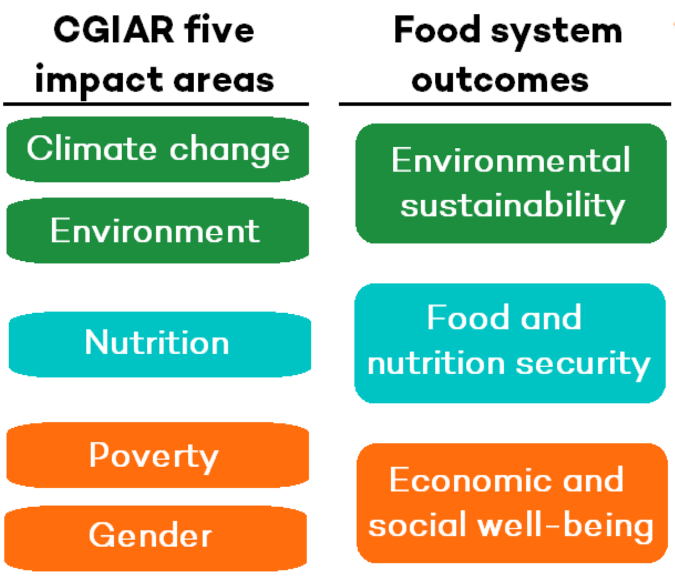

Figure 5. CGIAR impact areas linked to the key food system outcomes

CGIAR has five impact areas that outline the focus of their research strategy. In this foresight study we link the five impact areas to the three main food system outcomes in the food system concept we used for the analysis. The links between the impact areas and system outcomes are shown in **figure 5**. While this report aims to set out the environmental and climate change impacts, we argue these developments cannot be considered separate from the other impact areas as they are intertwined. As such, in the section below we outline impacts on each of the food system outcomes that can be mapped on the CGIAR impact areas.

4.2.1 Environmental sustainability

The way food systems are managed has major implications for environmental sustainability outcomes. Given the food systems' current inability to deliver on this crucial outcome, the scenario analysis can provide valuable insights.

Climate change

A key concern of the 21st century is our ability to halt climate change, while the impacts of a changing climate on food systems are becoming evident. Climate change is already impacting many biophysical processes and influences change in social systems. With respect to food systems, two key areas of concern are mentioned across the reports – namely, the need to continue with efforts to adapt food systems, and agriculture in particular, to changes in biophysical climate variables and more frequent extreme events, and the need to reduce the GHG emission profiles of food systems substantially via various supply- and demand-side measures.

With respect to adapting to climate change, the WRI assessed the results of various crop models on the stated potential for adaption across agricultural systems. WRI states that the evidence from crop models suggests significant capacity to adapt. But there is high uncertainty about the extent to which adaptation can offset the adverse effects of climate change, and it is doubtful that currently available forms of adaptation – although significant – can fully offset these adverse effects. In addition, some reports raise the question of where agriculture can take place and to what extent more predicable weather will result in stable food supplies.

All reports give much attention to total levels of GHG emissions and specifically to the food system's contribution of GHG emissions. Each report describes detailed approaches to bringing down GHG emissions but find various levels of success. Also, assumptions about emission reduction targets in line with the Paris Agreement differ, although 4 Gt CO_2 for food systems emissions for 2030 is seen as the limit (see **table 9**). Nevertheless, while all reports refer to the Paris Agreement as setting the target for emissions reduction to a maximum of 4 Gt CO_2 in 2030, all emphasise the need for net-zero-emissions food systems by 2050.

Notable in **table 9** are the different assumptions about the trajectory of baseline trends. Whereas FOLU expects GHG emissions to level out in the baseline scenario, WRI foresees an increase in GHG emissions owing to their adjusted population growth figures, which in turn demand more food production. This therefore also influences the pathways-of-change scenario, as WRI now must fill a larger gap towards the Paris Agreement target. Visible in the pathways-of-change scenarios is that all reports present a scenario that can meet the Paris target of 4.0 Gt in CO_2 emissions, of which two even represent net-zero-emissions food systems.

To make sense of what this means for the future of food systems, we must highlight some of the differences between the reports. 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. On top of that, the *Better futures* scenario assumes that global temperatures in 2050 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 emissions targets.

Table 9. CO_2 emissions from food systems in Gt as mentioned in the reports

Report	**Baseline** 2010	**Baseline** 2050	**Pathways of change 2050** Scen. 1	Scen. 2	Scen. 3	**Paris target** 2030
WRI		15.0	9.1	5.8	4.6 / **0.0**	
FOLU	12.0	13.0	**0.0**	-	-	**4.0**
EAT		9.8[1]	**4.0**	-	-	

[1] The EAT-Lancet scenario looks at food production only, distorting the baseline result. Nevertheless, the pathway of change scenario can be compared, given that it assumes that there will be no land-use change in 2050 – similar to FOLU.

In contrast, the objective of the WRI report is to tackle multiple global challenges, which include food demand, land use, and GHG mitigation. The 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 *high ambition* regarding both governance and technology is insufficient 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. They outline a further addition to the scenario which includes ecological restoration of much of the freed-up land, resulting in a net-zero-emissions scenario.

Status of land resources

As per the definition of sustainable food systems, the status of land resources should be maintained at a level where food production can continue without putting increasing pressure on ecological systems. This requires a balancing act, as these two activities present two sides of the same coin: food production relies on natural resources, while the status of natural resources relies on the way food is produced. In each of the reports, ample attention is given to the status of land resources and how to steer agricultural production into a more balanced direction.

Each report gives considerable weight to agricultural systems and their impacts on water systems, quality of the soil, and nutrient cycles. The baseline scenario of all reports shows that extra measures are needed in order to make sustainable use of water and soil possible, as the availability of freshwater for food systems and water pollution continues to be a serious issue. However, they see this as being connected to soil management and nutrient cycling. For example, WRI's baseline scenario shows that they assume improvements are made in terms of nutrient cycling and in turn soil quality even in the business-as-usual 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 freshwater available for food systems. The scenarios incorporate a variety of soil and water management practices that are assumed 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 systems perspective.

As cited a few times before, the amount of land available for agriculture is a main concern, especially because this is a variable that is static. The earth's surface is not expected to grow; rather, it is expected to shrink owing to rising seawater. The reports unanimously underline the intimate connection between agricultural land use and biodiversity and GHG mitigation. Clearing natural landscapes for agricultural production leads to loss of carbon sinks and wild biodiversity in flora and

Table 10. Scenario assessment of key food system outcomes in 2050 compared with current status

Key food system outcomes		Outcome variables	WRI				FOLU		WEF				EAT	
			Baseline	*Coordinated effort*	*Highly ambitious*	*Breakthrough technologies*	*Current trends*	*Better futures*	*Survival of the richest*	*Unchecked consumption*	*Open-source sustainability*	*Local is the new global*	*B.A.U.+ full waste*	*PROD+ + diet shift + ½ waste*
Food and nutrition security	Availability	*Total food production*	++	+++	++	++				+++				
		Yields	++	++	++	+++	+	++		++			+	+++
		Food loss and waste	o	-	--	---	-	--	++		-	--	+	--
		Food imports							---	+	++	+		
	Utilisation	*Food quality*					-	+	--	---				
		Nutritional health	--	-	+	++	--	++	--	---	++	+	--	+++
	Stability	*Food price volatility*							+++					
		Socio-economic shocks							++					
	Accessibility	*Food affordability*							---	+	--			
		Food distribution (national, local, household)	--	-	+	++	--	+++	---					
		Self-sufficiency					o	++			+			
Environmental sustainability	Climate change	*GHG emissions*	++	-	--	---	o	---	+++	+++	+	+	++	--
		Biophysical seasonal changes							+++	+++	+	+		
		Extreme events							+++	+++	+	+		
	Status of land resources	*Freshwater quality*						++	--	--	+	+		
		% freshwater availability for food systems	-	-	+	++	o	++	--	--	+	+	--	+
		Nutrient cycling	+	+	++	+++	-	++	--				---	+
		Soil quality	+	+	++	++	-	++		--	+		-	+
		Agricultural land use	+++	+	--	---	+++	--	+	++	+	+	+++	---
		Land fragmentation	+	-	--	---	+	---			--	-	++	---
		Wild biodiversity	o	+	++	+++	---	++	---	--	+		---	-
		Agrobiodiversity	+	++	++	++	-	++	---	---	+			
	Status of marine resources	*Wild marine biodiversity*	+	+++	+++	+++	--	++	--					
		Aquaculture production	+	++	+++	+++	++	+						
Economic & social well-being	Livelihood opportunities	*Number of jobs in food systems*					o	++	---					
		% of GDP from food systems							---					
		Farmers' income from food system activities					-	+	--	---	+	+		
	Equity considerations	*Gender*					o	+	--					
		Balanced relationships Global South & North					o	+++	---	+				
		Land tenure					o	++	--	---				

fauna. Land use fragmentation is considered a further pressure on biodiversity, as it would reduce natural landscapes to small patches, especially threating biodiverse fauna. The scenario-based food system outcome assessment shows this relation clearly and shows 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 emphasise that a decrease in agricultural land use opens space for wild biodiversity to flourish. FOLU and WRI specifically highlight the need for more agrobiodiversity as a strategy to promote more climate-adaptive agriculture.

Status of marine resources

A third essential outcome that needs to be secured for environmental sustainability relates to marine resources. The status of marine resources can be assessed through many components, but the link to food systems is especially expressed by wild marine biodiversity and aquaculture production. Increasingly, marine resources are emphasised as a sustainable option in the protein dilemma that results from growing food demand. Here aquaculture is considered a biodiverse-friendly option for increasing fish protein. However, the scenarios also emphasise a dual relation between marine harvesting of fish and aquaculture. While on the one hand an increase in aquaculture could relieve marine stocks, scenarios also emphasise 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 highlight the complex relations between wild fish stocks and aquaculture and propose putting protective measures in place against illegal fishing, ensuring fishing rights for small-scale fisherfolk, restoring fish stock to reproducing size, and innovating in the field of fish feed (e.g., using surplus material from the fish industry). Only with these measures can aquaculture grow sustainably without putting further pressure on wild marine biodiversity. 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.

4.2.2 Food and nutrition security

A key to the functioning of food systems is their ability to deliver on food and nutrition security. To operationalise this feature in the scenarios, we turn to the FAO definition of food and nutrition security, which sets out the following set of variables.

Availability

The first dimension shaping food and nutrition security is the availability of food. This can be assessed by monitoring the global production of food, the level of food loss and waste, and food imports. Notable across the scenarios is the need to increase yields of crops and livestock to meet the growing demand for food. All the intervention scenarios also emphasise the need to reduce food loss and waste, as well as increase yields, as a crucial element in meeting food demand. There is also unanimous emphasis on the need to increase total food production, but WRI's *breakthrough technologies* scenario shows how a significant reduction in food loss and an increase in yields will reduce the urgency of increasing total food production, freeing up space for other land uses.

Utilisation

The utilisation of food is characterised by food quality and by nutritional health. Nutritional health is 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 malnutrition leading to overweight and obesity. Each of the scenarios highlights the need to push nutritional patterns in more nutrition-secure and healthy directions. In WRI the emphasis is predominantly on a nutrition-secure population, reasoning from a perspective that meeting total food demand will be one of the major challenges in this scenario. 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 emphasising that nutritional health remains a major vulnerability on a global level.

Stability

Food prices and socio-economic shocks are a major influence on global food and nutrition security. The volatile food price situation during 2008–2009 caused food riots globally, as entire communities were suddenly unable to buy food and became food insecure. While the importance of these factors are acknowledged in both WRI and FOLU reports, the impact on food stability is not comprehensively assessed in these scenarios.

Accessibility

The final component of food and nutrition security is accessibility of food and leans heavily on the work of Sen (1981). To assess the accessibility of food, we look to food affordability, food distribution at various levels, and regional self-sufficiency. Little is said about actual food affordability: while FOLU stresses the need for more fair prices, WRI emphasises the need for more research into the role of food prices on both sustainability of diets and poverty. There is ongoing debate about the need for accessibility versus availability: some emphasise that sufficient food is currently produced and that the major problem is inequitable distribution of food, leading to surplus food in one place and hunger in another. Interestingly, all scenarios go beyond this debate and argue that the expected population growth urgently requires both. They also all emphasise that to improve food distribution, there needs to be better global coordination amongst actors to share knowledge and technologies beyond the currently existing relationship of dependency between Global South and Global North countries.

4.2.3 Economic and social well-being

The third key outcome of food systems focuses on economic and social well-being. We assess this by focussing on livelihood opportunities and equity considerations. However, the scenario-based assessments that lean on modelling have predominantly focused on the concrete impacts on food and nutrition security and environmental sustainability.

Livelihood opportunities

The reports echo the importance of food systems as a source for livelihood opportunities for a large part of the global population. They emphasise the importance of maintaining such job opportunities for food systems to 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 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 localised 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 emphasises the number of people that rely on agricultural practices for their livelihood and the necessity to carefully weigh options and see how they impact upon people's lives.

Equity considerations

The second crucial element in assessing economic and social well-being consists of equity considerations. Here we also 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.

For example, both FOLU and WRI emphasise 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 regionalised systems, gender equity will increase. FOLU expects that these localised systems will allow for more self-sufficiency, resulting 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.

5. Key trends and future food system impacts

5. Key findings

Climate change and environmental issues related to water, biodiversity, soils, and nutrient cycling are seen by the analysed reports as the most important drivers changing food systems. The reports also highlight how these drivers are inseparable from other key factors such as technological change (especially disruptive technologies), societal changes (such as dietary change), market dynamics, and ways to govern food system activities. They suggest a plethora of responses to address these food system drivers, most of which are geared towards specific impacts on specific food system activities (see the **Annex** for an overview of responses across food system activities). The responses include new technologies, changes in practices, and changes in consumption patterns. Much less is said in the reports about how to respond to market dynamics or food system governance issues, and they mention few innovations that address the 'missing middle' of food systems (processing, retail, trade etc.) except in the GAIN report. Here we provide a summary of the main findings across all analysed reports.

5.1 Climate and environmental issues

The continuing need for adaptation

The analysed reports show that climate change impacts on food systems will continue or even worsen. Therefore, they see a need for food systems across all regions of the globe to continue with efforts to adapt to the potential changes. 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.

The need to change the emissions profile of food systems

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 adaptation and the need for reducing the environmental footprint

With respect to both climate change and other environmental changes such as water scarcity or the loss of agro-biodiversity, agricultural practices will have to adapt. At the same time agriculture and the wider food system are called upon to reduce their GHG emissions profiles and wider environmental footprint. Balancing both goals, particularly in a developing-country context, requires careful navigation of priorities and new technologies and incentive structures.

Pressures on agricultural land management and expansion

Growth in food demand will continue to put pressure on land resources in the future, resulting in various agricultural land expansion scenarios. This pressure is exacerbated by poor agricultural land management that results in soil degradation. The scenarios show varying degrees of expansion and varying impacts on biodiversity, nutrient cycling, and water resources, depending on how management and expansion happen and where. 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 to meet growing food demand.

5.2 Technological innovations

Integrated menu of options

All reports see technological innovations as a key part of the solution for food system change. Options across all food system activities are needed, from the agricultural system (e.g., breeding, regenerative agriculture) to changes in consumer behaviour (e.g., nudging via changed food environments, labelling). WRI and FOLU show how innovations in one part of the system could and should be coordinated with other parts of the food system to enable transformative change. This consideration emphasises the need to consider the impacts of changes for a specific food system innovation on all other parts of the system, requiring a food system perspective. What the reports are less clear on, though, is what governance arrangements might be needed to achieve coordinated transformation.

Accessibility of new technologies

Various studies stress the need for innovations to be widely available at accessible prices, signalling equity concerns. Many of the innovations expand on existing innovations, but a number of disruptive technologies (e.g., precision fermentation, Internet of Things) are also described that could have far-reaching implications for specific food system actors. As political and market dynamics can play an important role in shaping food systems in a more equitable way, the reports raise the question of how to best govern innovation systems so that they provide wide access to new technologies. This also includes the issue of research funding and how it shapes the types of technologies available to various actors.

5.3 Dietary change

Healthy and sustainable diets

Dietary change towards better nutrition, as opposed to only meeting caloric needs, is seen as a key lever for overcoming the triple burden of malnutrition. Healthy and balanced diets need to include more fruits, vegetables, and nuts. Furthermore, a move away from meat and the inclusion of new protein sources from plants, insects, precision fermentation, etc., are demanded by increasingly environmentally conscious consumers. Studies vary in their emphasis on this topic, with some studies focusing on identifying the most ecologically appropriate dietary change (FOLU 2019; EAT 2019), while others assess the ecological potential of diets (WRI 2019). While the studies paint a picture of what dietary change constitutes at a global level, less clear is what this might mean on a regional level. Insights about dietary change in different regions are necessary for developing pathways of change that respect local needs, context, and culture. This would put emphasis on the question of what we can ethically demand from more vulnerable communities and what equitable change processes entail. This remains a major gap in food systems science and requires more research.

A quest for alternative protein

Most of the reports signal a need to find alternative sources of protein, for both health and environmental reasons. Aquaculture is seen as a growing contributor to supplement fish demand as wild-caught fisheries stagnate. FOLU signals a trend showing that the mariculture production of bivalves (including oysters, clams, and molluscs) could reach double the size of today's global wild fish capture, solving a major part of the protein challenge. Aquaculture is also seen as a threat to land use, as feed supplements are increasingly grown on land, competing with agriculture for resources. None of the reports explore other alternative protein sources (i.e., insects, algae, plant-based proteins) beyond mention. A disruptive technology for protein generation with potentially wide-reaching consequences – precision fermentation – is presented by the RethinkX report based on the convergence of biological and information technology.

5.4 Just transitions

Many of the reports embed the need for just transitions in food systems, in which food and nutrition security outcomes are delivered in an equitable manner. The reports do not elaborate on how this should be achieved but rather make assumptions about achieved equity. For example, the FOLU report makes the assumption that their proposed pathway to sustainable food systems will ultimately lead to more equitable food systems, while WRI only portrays scenarios where food demand is met and food is more equitably distributed. While they highlight the importance of equity, the reports say less about how to bring about the envisioned changes in food systems in order to achieve it. There are signals throughout the reports that attempt to link to equity considerations, such as the emphasis on making innovations accessible. Nevertheless, WRI cautions that population growth is underestimated (the report shows that fertility rates have not gone down as quickly as expected), which compromises the ability of food systems to plan for equitable outcomes. This situation will exacerbate the pressure on the world's ability to meet food demand in a sustainable and equitable manner.

A major challenge that is left unaddressed across the reports is how to further a just sustainability transition and support the potential losers from a change towards sustainability. Some of the reports (ISPC 2018; FOLU 2019) point to current challenges created by ongoing concentration processes in the food sector – for example, land acquisitions or mergers in the seed and retail sectors, and notions of moving agriculture to the most productive regions (i.e., linking agricultural production efficiency and conservation), which will threaten livelihood opportunities, particularly for smallholder farmers.

6. The role of CGIAR

6. The role of CGIAR

This section discusses the potential role that CGIAR could play in addressing the challenges to food systems in the future, as identified in the analysed foresight reports. CGIAR is well positioned to address some within its current set of activities, while others would require extending or reshaping its focus.

6.1 Recommendations for CGIAR

Can adaptation 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 if current efforts can keep up with expected impacts across countries and agro-ecological zones.

> *CGIAR has longstanding experience with developing adaptation practices. It needs to continue its work on adaptation and support innovation processes to keep up with expected climate change impacts. Moreover, CGIAR can contribute to the development of more contextual pathways to adaptation measures, as this cannot be done via a global blueprint.*

Navigating climate change 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 developing countries 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.

> *With respect to the balancing of adaptation and mitigation options for the food sector, knowledge and insights into the country context are needed, as well as an understanding of biophysical dynamics and technology options. CGIAR is well positioned to support country partners in exploring difficult choices and adjusting innovation systems to develop appropriate technologies and policy options.*

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. 2020). Finding solutions in a way that includes marginalized voices in the debate will be key for transitioning towards equitable and economically sound food systems.

> *Based on CGIAR's long-standing relationships with a wide range of food system actors, the organisation can convene and foster much-needed debate on contentious issues and trade-offs prevalent in the contemporary and future food systems with current and new partners.*

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 socio-economic 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 contextualise these globally determined diets, making them sensitive to local cultures, ecosystems, and resource availability.

> *CGIAR can contribute to addressing the knowledge gap on how to contextualize dietary shifts in a manner that is ethically and culturally appropriate. A focus on better nutrition can offer new opportunities to CGIAR while balancing its current focus on staple crops. This could build on CGIAR's experiences around nutrition and land use management.*

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 practises.

> *There is an opportunity for CGIAR to expand towards an investigation of new sources of protein, from fish and mariculture as well as from plant-based sources. Here the reach and experience of CGIAR in implementation of programs would provide the infrastructure needed to make these techniques accessible.*

Trade-off analysis and foresight work

As emphasised 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.

> *CGIAR could provide foresight and trade-off analysis tools and methods as well as space for dialogue internally and with different partners – for example, linked to further activities of the Global Futures program or CCAFS. This could be done both on a global level and on a country or regional level to enable coordinated strategies among multiple partners and CGIAR.*

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.

> *For CGIAR, this wider food system focus can shape a comprehensive research focus and enlarge the set of partners to include in research and research priority setting.*

6.2 Research gaps that could be addressed by the ISDC

While the reviewed foresight exercises address a wide range of trends shaping food systems in the future, there remain several gaps in the analysed studies. Here we provide a few thoughts on topics that the ISDC could explore with future research.

Some of the analysed studies point to emerging disruptive technologies becoming available through, for example, the convergence of biological and information technologies, new artificial intelligence mechanisms, and the availability of 'big data' in agriculture and value chain management. A systematic assessment of these disruptive technologies with respect to their opportunities and challenges is needed to determine how they will affect the food systems, particularly of developing countries. Because of their newness, it is unclear how they will develop in different country settings, and the reports merely speculate on their potential impacts.

While impacts of changing physical climate variables are discussed in various studies, impacts of climate change on crops and livestock pests and diseases have received much less attention in the foresight studies. While they are sometimes mentioned under the umbrella of needed adaptations for the food sector, their impacts are not discussed in detail and would warrant further attention, especially as CGIAR has core competencies in this area.

Dietary change towards better nutrition (more fruits and vegetables) as well as more environmentally friendly choices (new protein sources) is seen as a key lever for change, though the implications of different options for achieving this are only partly explored across the studies. This remains a major gap in food systems research and requires more research.

The analysed foresight studies mainly explore various technological options to deal with climate change, environmental concerns, and other driver impacts on food system activities and their outcomes, while policy change and new governance arrangements are less explored. The role of new policy instruments (such as taxes, price mechanisms), new governance arrangements, or other options for incentivizing food system change need to be explored with their implications in specific country settings.

7. References

7. References

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Annex

I. **Innovations across the food system**

	FOLU	WRI	GKI	RethinkX	WIPO	GAIN	WEF	NAP
Innovations in crop production	Regenerative agriculture; Plant-based proteins	Breeding; Agroforestry & water harvesting; Cultivate fallow lands; Low-carbon & environmental-cost crops; Biological nitrification inhibition; Variety selection & improved water & straw management	Microbes for agriculture; Early warning systems for plant disease and pests		Breeding desired traits; Biofertilizers, culturing; microbes for soil amendment; biocontrol, biopesticides, breeding and genetic engineering; Fermentation of biofuel feedstock	Fortified crops; Mushroom and fungus cultivation; Millet-based foods; Plant-based protein alternatives; Data-driven vertical farming; Crop disease diagnostic apps; Harvest robots; Nutri-gardens; Local and indigenous crops; CRISPR gene editing	Alternative proteins; Precision agriculture; Gene editing for traits; Microbiomes; Biocontrol & micronutrients for soil management	Gene editing; Microbiomes; Sensing technologies & data analytics for nutrient monitoring; Improve agronomic practices; Research in soil sciences, technology adoption, and community engagement
Innovations in livestock production	Controlled livestock grazing; Insect-based proteins	Improve feed quality, grazing management; Reduce ruminant methane; Reduce emissions from concentrated animal production; Biological nitrification inhibitors for pastures		Program micro-organisms to produce precise proteins, fats, and vitamins at marginal costs	Breeding, genetics, cloning & stem cell technologies; Biologics, vaccines, & biological approaches to diagnose, prevent, and treat disease; Feed processing & feed supplements	Ingestible sensors; CRISPR gene editing		Gene editing/ precision breeding; Microbiomes to improve feed efficiency; Data-driven approaches to disease detection and prevention; Animal welfare & precision livestock; Promote consumer-informed purchasing decisions

	FOLU	WRI	GKI	RethinkX	WIPO	GAIN	WEF	NAP
Innovations in seafood production	Aquatic proteins	Stabilize size of wild fish catch by reducing overfishing; Aquaculture production through breeding, feeds, health care, disease control, and changes in production systems		Program micro-organisms to produce precise proteins, fats, and vitamins at marginal costs		Microalgae and seaweed-based foods; Alternative fish feed		
Innovations in food processing	(Re)design products based on human and planetary health; Develop laboratory-cultured protein production		Cooperative packaging; Modular factories; Near-farm mobile processing; Dehydration for smallholders		Biological applications in milling, separation, ingredient formulation, fermentation	Farm-level sorting, grading, and packaging; Food safety robots; Cassava curing bags; Ethylene absorption; Low-cost solar dryer; Modular factories; Near-farm mobile processing; Solar mills; Value-added surplus products; Cooperative packaging		Improve processing and packaging technologies; Apply 'foodomic' technologies; Validate advanced food-processing and packaging technologies.

	FOLU	WRI	GKI	RethinkX	WIPO	GAIN	WEF	NAP
Innovations in trade	Transparent & deforestation-free suppliers and supply chains		Crates adapted for smallholder supply chains; Biodegradable coatings; Improved traceability technologies; Farm-to-fork virtual marketplace			Online freight forwarding; Predictive supply chain analytics; Real-time freight and logistics services; Logistics services	Internet of Things for real-time supply chain transparency and traceability; Blockchain-enabled traceability; Food-sensing technologies for food traceability	
Innovations in storage			Mobile pre-cooling & packhouses; On-farm solar preservation; Micro cold transport; Adaptable reefer containers; Cold chain as a service; Micro-warehousing & shipping; Evaporative cooling systems			Zerofly storage bags; Cellulose crafting and packaging; Cold plasma; Edible films and coatings; Edible packaging; Smart refrigerators; Frozen food delivery system; Pricing models based on freshness; Smart packaging; Starch-based coatings; Mobile pre-cooling and packhouses; Smallholder milk containers; Small/micro-scale cooling (solar, evaporative, boxes, refrigerated transport)		

	FOLU	WRI	GKI	RethinkX	WIPO	GAIN	WEF	NAP
Innovations in retail			Improved traceability technologies; Specialty marketing for PHL-prone crops; Farm-to-fork virtual marketplace			Online farmers' markets; On-demand food shopping; Sharing economy for produce delivery; Subscription-based food delivery services; Last-mile milk dispensing; On-demand third-party logistics; Autonomous transport; Automated supply chain services	Mobile service delivery	
Innovations in consumption						Nutrigenetics; Nutrigenomics; Personalized nutrition	Nutrigenetics for personalised nutrition	Enhance consumer appeal in a cost-effective and efficient manner; Consumer understanding & acceptance of innovations through expanded knowledge about consumer behaviour and risk-related decisions and practices

	FOLU	WRI	GKI	RethinkX	WIPO	GAIN	WEF	NAP
Innovations in waste						Real-time food safety analysis; Secondary markets for food waste; Food safety robots	Food-sensing technologies for food safety and quality	Provide enhanced product quality, nutrient retention & safety; Capitalizing on new data analytics, data integration, and the development of advanced decision support tools to reduce food loss
Innovations in finance			First-loss capital guarantee for post-harvest loss			Financing of innovations; Kickstarter-supported agriculture; Market brokerage via mobile devices; Smart contracts; Training and certification for informal markets		

	FOLU	WRI	GKI	RethinkX	WIPO	GAIN	WEF	NAP
Innovations in governance	Establish planetary and human health dietary standards; Scale up payments for ecosystem services; 'Moratorium' on conversion of natural ecosystems; Legal rights for indigenous peoples; Scale up REDD+ and global alliance against environmental crime; Protect breeding grounds and end illegal fishing; Provide access rights to artisanal fishers; Increase R&D spending in alternative proteins & ensure intellectual property stays in the public domain; Use public procurement to secure long-term offtake of alternative protein sources; Regulate and incentivise companies to report/reduce food loss and waste; Foster local circular food economy through targeted public procurement and zoning	Legally link productivity gains in agriculture to governance that avoids agricultural expansion; Protect native landscapes; reforest abandoned, unproductive, and unimprovable agricultural land; Avoid conversion of peatlands to agriculture, and restore little-used, drained peatlands by rewetting them				Blockchain; Crowd-sourced information sharing		Support improved decision making to maximize food integrity, quality, safety, and traceability; Address privacy concerns and incentivise sharing of public, private, and syndicated data

	FOLU	WRI	GKI	RethinkX	WIPO	GAIN	WEF	NAP
Other innovations	Invest in maternal and child health and nutrition & education for women and girls; Ensure access to reproductive health; Rural roads and digital investments; Renewable electricity access for all	Shift to renewable energy; Sequester carbon in higher crop and/or pasture productivity, and do not sacrifice carbon storage elsewhere	Behavioural economics for agriculture; Battery technologies; Mobile education centres			Bioplastics for agriculture; Edible RFID tags; 3D printed food; AI-powered nutrition; Cellular agriculture; Microbiota-directed foods; Aflatoxin detection; Algorithm nutrition apps; Hyperspectral imagery; Microbial data–based interventions; Neural networks and deep learning; Augmented reality for product information; Nanomaterials; On-demand mechanization; Commercial drones; Solar pumping	Big data and advanced analytics for insurance; Off-grid renewable energy and storage	TD research & systems approach; Develop sensing technologies; Agri-food informatics; Water-saving technologies across integrated systems; Digital infrastructure

II. Terms of reference

TERMS OF REFERENCE
Food and Agriculture Systems Foresight Study
Synthesis through Desk Review
(Level of Effort 35 days)

Background and Context

CGIAR is a global scientific research-for-development partnership consisting of the System Organization, Centers, CGIAR Funders, and Partners to implement its Strategy and Results Framework (SRF). CGIAR is undergoing a reform towards One CGIAR. Under this reform, CGIAR will develop a 2030 Research Strategy anchored in a unifying mission of "Ending hunger by 2030 – through science to transform food, land and water systems in a climate crisis," focused on five Impact Areas of nutrition, poverty, gender, climate, and environment.

As a prelude to the current reform of CGIAR, the Independent Science for Development Council was created, being a reformulation of the mandate of the past Independent Science and Partnership Council (ISPC). The ISDC delivers according to a CGIAR System Council-defined Terms of Reference. Its membership has been defined as of October 2019. In order to operate, the ISDC receives the operational support of CGIAR Advisory Services Shared Secretariat (CAS Secretariat), hosted at the Rome, Italy, office of the Alliance of Bioversity International and the International Tropical Agricultural Research Center.

Assignment Details

The ISDC is seeking expert consultants with experience in applied research for development and long-term strategic thinking, in particular in one or more of the domains of food and agriculture systems (nutrition, poverty, gender, climate, and environment) that are identified impact areas of One CGIAR. Under the overall thought leadership and guidance of ISDC Member Professor Chris Barrett and under the operational supervision of CAS Secretariat Director Allison Grove Smith, the expert consultants will conduct a desk review that aligns and translates the agriculture and food systems foresight work of ISPC and other actors within and without CGIAR to clusters of specified Impact Areas of CGIAR.

The ISDC is especially interested in translating the considerable mass of recent high-quality foresight studies to the new One CGIAR context, deploying science to transform food, land and water systems in a climate crisis with a tight focus on specific impact areas. The objective is not new foresight work but rather synthesis and translation of existing work to help inform CGIAR research strategy to 2030.

The deliverable expected is a report of 15- 25 pages (not including citations) with a 2-page executive summary. Leading a presentation and discussion of the content with ISDC and guests at the ISDC April meeting is required.

Two desk studies will be commissioned. The first will focus on the implications of recent foresight studies for CGIAR research for development as it relates to impact areas of nutrition, poverty and gender. The second will focus on the implications of recent foresight studies for CGIAR research for development as it relates to impact areas of climate and environment. ISDC recognizes that there is overlap in these areas.

In particular, the consultant for the Environment and Climate Change Foresight Synthesis will:

- Undertake a critical desk review to synthesize existing analyses through the lens of climate and environment impacts on which the One CGIAR will focus, with a horizon to at least 2030 or beyond, drawing in particular on:
  - ISPC-sponsored foresight work from 2016-2018, culminating in R. Serraj and P. Pingali, eds. (2018), *Agriculture and Food Systems to 2050: Global Trends, Challenges and Opportunities*.
  - CGIAR-sponsored foresight and ex ante impact assessment work, in particular under Global Futures and Strategic Foresight https://globalfutures.cgiar.org/project-overview/.
  - Agri-food systems foresight and ex ante impact assessment work by selected other leading organizations, including, but not limited to:
    - Committee on World Food Security High Level Panel of Experts on Food Security and Nutrition (CFS HLPE), various reports available at http://www.fao.org/cfs/cfs-hlpe/reports/en/
    - Food and Land Use Coalition (FOLU, 2019), Growing Better: Ten Critical Transitions to Transform Food and Land Use (2019).
    - Global Knowledge Initiative and Rockefeller Foundation (2017), Innovating the Future of Food Systems.
    - Graff, G.D. and I. Hamdan-Livramento (2019), Global Roots of Innovation in Plant Biotechnology (World Intellectual Property Organization).
    - Hansen, A.R., Keenan, C., and Sidhu, G. (2019). Nutritious Food Foresight: Twelve ways to invest in good food in emerging markets. Global Knowledge Initiative and Global Alliance for Improved Nutrition.
    - National Academies of Sciences (2019), Science Breakthroughs to Advance Food and Agricultural Research by 2030.
    - RethinkX (2019), Rethinking Food and Agriculture 2020-2030.
    - World Economic Forum (2018), Innovation with a Purpose: The role of technology innovation in accelerating food systems transformation.
    - World Resources Institute (2019), World Resources Report: Creating A Sustainable Food Future.
- Author study of 15-25 pages that (i) defines different scenarios for agri-food systems evolution over the coming 10-25 years, recognizing likely variation across agroecological and socioeconomic contexts, (ii) synthesizes the findings of prior foresight and ex ante impact assessment work through the lens of climate and environment impacts, (iii) identifies key prospective roles – and specific innovation spaces – for CGIAR in those scenarios, and (iv) highlights gaps in foresight work that ISDC might explore in the coming 2-4 years. The study should include complete citations and references for key innovations and findings.
- Prepare a two-page executive summary that points to the strategic planning implications of foresight work.
- Present the findings in a meeting with ISDC members in April.
- Arrange three virtual meetings during February and March with Prof Barrett and Professor Lesley Torrance to update on progress and discuss emergent findings and themes.


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