# Science for Transformation of Food Systems: Opportunities for the UN Food Systems Summit

**Joachim von Braun, Kaosar Afsana, Louise O. Fresco, and Mohamed Hag Ali Hassan**

## 1 Introduction

Food systems (von Braun et al. 2021a) at the global level, and in many countries and regions, are failing to end hunger, provide adequate nutritious foods for healthy diets, or deliver safe foods. Between 720 million and 811 million people face hunger and are undernourished – that is, every tenth person – 150 million children under 5 years of age are stunted (short for their age), and two billion people are overweight or obese. These numbers have been high and/or growing for a number of years now, and with COVID-19 disproportionately impacting poor and food-insecure populations, they are continuing to rise, with an estimated 118 million more people facing hunger in 2020 than in 2019 (FAO et al. 2021; Klassen and Murphy 2020). About 600 million people fall ill each year due to the consumption of contaminated or unsafe foods (WHO 2020). We are losing ground on the progress that we have already made, and we face the prospect of severely compromising the achievement of the SDGs and the 2030 Agenda.

J. von Braun (✉)
Center for Development Research (ZEF), University of Bonn, Bonn, Germany
e-mail: jvonbraun@uni-bonn.de

K. Afsana
James P Grant School of Public Health, BRAC University, Dhaka, Bangladesh

L. O. Fresco
Wageningen University and Research, Wageningen, The Netherlands

M. H. A. Hassan
The World Academy of Sciences for the Advancement of Science in Developing Countries (TWAS), Trieste, Italy



J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_50

Besides escalating hunger and all forms of malnutrition (micronutrient deficiencies, underweight, overweight/obesity and related NCDs), poverty and inequalities between and within countries are widespread and becoming entrenched. For many people, engaging in activities in the food system would seem to offer the most viable opportunities to escape poverty, yet they are being left out of earning their fair share of the benefits from engaging in food systems, and are condemned to jobs that do not provide livable wages and decent working conditions and livelihoods. Fundamental human rights to food, health, safe water and sanitation, and education continue to be violated. Ending poverty and gross inequalities remains essential for achieving the SDGs.

Food systems relate to the three basic dimensions of sustainability: social, economic, and environmental (Dury et al. 2019; FAO 2018). Many food systems are based on production and distribution systems that are simply not sustainable. Scientific assessments indicate that many aspects of current food production systems drive the degradation of land and soil, water, and climate, as well as biodiversity loss (IPBES 2019; HLPE 2017). Climate change is increasingly adversely impacting food security. The global food system emits about 30% of global greenhouse gases, contributes to 80% of tropical deforestation, and is a main driver of soil degradation (Food and Land use Coalition 2019) and desertification, water scarcity, and biodiversity decline. Climate change, along with soil and environmental degradation, is partly caused by – and has negative impacts – on the food system. It is very clear that how we produce and consume food has profound implications for the health of people, animals, plants, and the planet itself (Bron et al. 2021).

The Food Systems Summit took place in the midst of the COVID-19 pandemic, which has revealed the close intertwining of food, ecological, and health systems (Webb et al. 2020a). The pandemic is having a significant impact on the global commodity markets and trading systems, economic growth, incomes, and poverty levels, with disproportionate burdens on vulnerable communities in both urban (Moustier et al. 2021) and rural areas. This is likely to worsen inequalities and undernutrition, including child undernutrition, which can have life-long consequences. Modeling projects that COVID-19 could result in an additional 9.3 million children wasted (low weight for height) and 2.6 million children stunted (low height for age) by 2022 (Osendarp et al. 2020). COVID-19 further increases food insecurity and poverty, which may become much more serious if comprehensive policy responses – especially equitable global vaccination coverage – are not implemented in a timely and evidence-based manner (von Braun et al. 2020).

Science needs to explore the root causes of emerging zoonotic diseases and closely engage with policy innovations, including those related to land use and animal production. Going forward, it is abundantly clear that more attention will need to be paid to how to make food systems more resilient to health shocks and pandemics, associated economic shocks and slowdowns, and violent conflicts and other crises, just as more attention is now being paid to how to make food systems more resilient to extreme weather events and other stressors induced by the changing climate (Webb et al. 2020b; Mushtaq et al. 2020). This will require integrated approaches that create greater synergy across government efforts to deal with health and other social services, as well as food system failures, in rural areas and other marginal communities (Allen et al. 2014; Wouterse and Badiane 2019).

The changing state of the art of science and innovation and the important lessons that they offer for food system transformation, need to be recognized. As noted earlier, science has at least two important roles in food systems: first, science generates new breakthroughs that can become innovations in food systems (e.g., genomics, plant nutrition, animal production and health, bio-sciences, earth sciences, social sciences, remote sensing, AI and robotics, digitization, big data, health and nutrition science, behavioral research, etc.); and second, science helps to inform and shape decisions, investments, policies and institutions, and can also be involved in the design, implementation and monitoring of actions needed to learn and draw lessons for impact at scale (Hainzelin et al. 2021). This also includes science that focuses on knowledge gaps, risks, uncertainties, and controversies. Many approaches, from discovery research to implementation research, and including both primary research and modeling techniques, can contribute valuable evidence.

## 2 Opportunities for Science and Innovation

Science and research are fundamental drivers of innovation. All three – science, research, and innovation – are essential for accelerating the transformation to healthier, more sustainable, equitable, and resilient food systems (Fears and Canales 2021). To enable the full inclusion of poor and marginalized populations – including smallholder communities (Diao et al. 2021) – in the process of and benefit from food system transformation, investments in technology-based innovations must be accompanied by institutional innovations (including social, business and policy innovations), underpinned by science: basic sciences and applied sciences, natural sciences and social sciences. The Scientific Group underlines not only its respect for Indigenous Peoples (von Braun et al. 2021a) knowledge systems, but also recommends investing more in programs that explore mutual learning and innovation across traditional and modern knowledge and science systems, considering both on equal footing. This may include documenting this knowledge and jointly studying it scientifically.

We highlight the need for systems innovations, rather than merely single-issue innovations, and call for enhanced collaboration between and among different disciplines of sciences for this purpose. We suggest a focus on seven science-driven innovations to catalyze, support, and accelerate food system transformation to achieve the SDGs, and SDG2 in particular. These innovations emerge from our conceptual framework and the building blocks and linkages therein (see Box). We hasten to emphasize that technology-based innovations and policy and institutional innovations are in synergy among each other: in other words, many technology-based innovations need policy and institutional innovations to fully realize their potential (for instance, innovative financing mechanisms), and, similarly, many policy and institutional innovations need technology-based innovations to be properly implemented and monitored (for instance, information systems). Further, in many instances, food system innovations must be place-based, adapted to the local contexts and capacities. We provide *examples of science-based innovations in the seven action areas below, identifiable in cursive format*. Alignment of technological change with sustainability concerns certainly requires attention and joint engagement by researchers from all areas of the food system-related sciences (including social sciences) guiding innovation arrangements.

## *2.1 Innovations to End Hunger and Increase the Availability and Affordability of Healthy Diets and Nutritious Foods*

More than three billion people cannot afford healthy diets, and more than 1.5 billion people cannot even afford a diet that only meets the required levels of essential nutrients (FAO et al. 2021; Masters et al. 2021). The contribution of science and innovation here relates to identifying optimal context-specific investment opportunities and their implementation. Broadly speaking, the investment opportunities include productivity enhancement, people's skills and empowerment, agricultural research, social protection, nutrition programs, etc. (Center for Development Research (ZEF) of the University of Bonn in cooperation with the Food and Agriculture Organization of the United Nations (FAO) 2020). Policy innovations are needed to *repurpose subsidies towards related supportive investments that facilitate a sustainable food system* (Hendriks et al. 2021a).

**Food Is Undervalued** The value of food from the cultural, social and economic perspectives needs revisiting. An important role of science here is also to identify the indirect effects of these perspectives, while efforts must be made to embrace the true value of food (Hendriks et al. 2021b). External costs associated with climate change (Hansen et al. 2019), biodiversity loss, and adverse health effects need to be considered. The current costs of environmental and health externalities of food systems are estimated to range within 4–11 trillion USD and 3–39 trillion USD, respectively. Compared to the current total global food consumption of nine trillion USD, the true cost of food, including environmental, health and economic externalities, is 19.8 trillion USD.[1] *True-cost accounting* approaches are to be pursued throughout the whole food system, and related capacities built up in the corporate and public sectors. Capacities for internalizing such externalities are limited.[2]

[1] https://sc-fss2021.org/wp-content/uploads/2021/06/UNFSS_true_cost_of_food.pdf

[2] It should be noted that lower food prices – if they come about in the short term – might have adverse income effects for producers and discourage them from investing to protect the ecosystem, especially if ecosystem services related to food systems are not incentivized, but more relevant is the avoidance of extreme price volatility, because that reduces incentives to invest and hurts farm households.

Cautious approaches are warranted to develop price and non-price instruments, including regulatory-based instruments, to help deal with such externalities. Fostering positive externalities of the food systems, such as through carbon farming and biodiversity-enhancing land use, should be considered and tested where justified (Miller et al. 2016). Nonetheless, if food prices were to reflect true costs, healthy diets may become unaffordable for low-income consumers, and social safety nets would need to be put in place.

**Healthy Diet Concepts Benefit from a Strong Scientific Basis** Measures that incentivize the production and market supply of fruits and vegetables and related innovations enhance consumption and can increase the income of smallholders (Zilberman et al. 2019; Zarnowiecki et al. 2020). However, rising incomes for consumers do not automatically lead to the increased consumption of healthy diets: even when accessibility and affordability are not constraints, the consumption of healthy diets is not assured, as people may still not change their consumption behavior. Approaches to creating demand for healthy diets and nutrition must be explored. At the same time, we have to be careful not to put all of the blame for poor nutrition on consumer behavior (Herrero et al. 2021a). Considerably more science is needed to understand the drivers in the processing, marketing and food environments. Science-intensive and promising opportunities such as *scaling up sustainable cold chain technology* to make perishable foods (especially fruits and vegetables, e.g., potatoes) more available and affordable (Harris et al. 2021) and, at the same time, reduce food loss and waste must be pursued, along with complementary *investments in infrastructure to reduce transportation and other related costs*, and thereby reduce food prices (van Zutphen et al. 2021).

**Nutrition Science – Like All Science – Is Conflicted**, and much of our real understanding of these nutrition issues is only starting to emerge. More research is needed to identify the most adequate healthy diets and their affordability and environmental sustainability across different contexts (Hirvonen et al. 2020; Headey and Alderman 2019). *Dietary targets* elaborated by the World Health Organization (WHO) – such as those related to adequate fruit and vegetable consumption, sweeteners, etc. – should be considered accordingly. There is a lack of scientific consensus on the dietary recommendations for animal-sourced proteins (ASF); these are nutrient-rich, but some are evidenced to increase the risk of diet-related chronic diseases if consumed at high levels. Plant-based diets have been evidenced to lower the risks of non-communicable diseases, and meet protein and adult micronutrient requirements. Changes in the consumption of ASF – reducing consumption, in particular, of processed forms of meat in communities where current levels are high and increasing consumption among vulnerable groups – can ensure a sustainable livestock sector while retaining the positive nutritional impact of ASF (Herrero et al. 2021b). Plant- and insect-based meat alternatives and protein sources can substitute for ASF without compromising its nutritional benefits. Improvements in the scientific assessment's methods regarding the health-related, environmental and socioeconomic impacts of reduction in ASF are needed. A potentially very significant contribution to deepened insights around the health-related aspects of diets is *the "Periodic Table of Food Initiative (PTFI),"* a global effort to create a public database of the bio-chemical composition and function of the food that we eat using the latest mass spectrometry technologies and bioinformatics.[3] If then combined with the *micro-biome science of human nutrition* (Kau et al. 2011), the perspectives on healthy diets may further shift and related health and information actions can become more concrete, including for the prevention of obesity.

We need to better understand how to *design and implement policies that enable healthy food environments, especially for children*, such as through taxes on foods whose excessive consumption should be avoided, limitations on advertisements of unhealthy foods, information through *educational food labeling,* prohibition of trans-fats, and regulation of the use of high-fructose corn syrup. Sound implementation of nutrition education is likewise required. Information about health properties from the industrial fortification and biofortification of certain foods should also be considered (Zilberman et al. 2019; Zarnowiecki et al. 2020; Downs and Demmler 2020). Research on the costs of action versus no-action regarding the key drivers of diets and food system change and the impact of these changes is required for effective decision-making.

## *2.2 Innovations to De-Risk Food Systems and Strengthen Resilience*

In particular, for negative emission farming, and drawing on both advanced science and traditional food system knowledge (Mirzabaev et al. 2021). As food systems become more global, dynamic, and complex, they also become more vulnerable to new, challenging, and systemic risks, as evidenced by the food price crisis in 2008, the ongoing COVID-19 pandemic (Sperling et al. 2020), and the performance of these systems during armed conflicts (Kemmerling et al. 2021). The implementation experiences of *triple nexus approaches of the humanitarian-peace-development nexus* should be accompanied by evidence-seeking social science (Barakat and Milton 2020). Science-based responses to catastrophes require preparedness. The capacity to understand, monitor, analyze, and communicate vulnerabilities, crises, and risks must be strengthened (Bhutta et al. 2013; Hidrobo et al. 2018; Ruel et al. 2013). Opportunities to expand and *improve food security forecasting and monitoring with web-based approaches* must be seized. Local *meteorological capacities must be expanded*, as accurate weather forecasting is of critical importance to farming communities. Food systems can be de-risked through *solar powered*

[3] See at https://foodperiodictable.org/about/

*small-scale irrigation* and affordable *smart phones with location-specific soil and weather data*, concrete innovations that can be scaled.

Food prices currently show fast upward movement and increased volatility. Such tendencies, on top of the income losses due to COVID-19, add to food security dangers for the poor. Care must be taken to avoid erratic policies, especially trade policies. While *strategic food reserves can play a role* in ensuring resilience to supply shocks, open rule-based trade – both international and interregional – can provide a more economical option for dealing with localized extreme weather events. Ensuring *free and rule-based open food trade* will require a rejuvenation of multilateral trade negotiations. In addition, to avoid panic-induced world price spikes, transparent information on production, stocks and government interventions around the world are critical and must be made widely available. The Agricultural Market Information System (*AMIS) is an important step* in this direction (Zimmermann and Rapsomanikis 2021).

Climate change is the defining issue of our time (Hodson et al. 2021; Hertel et al. 2021). Agriculture, deforestation and related land use change are the single largest drivers of multiple environmental pressures, and major contributors to greenhouse gas emissions. The livestock sector is also a major contributor of greenhouse gas emissions (Herrero et al. 2016). Significant improvements in livestock production productivity in terms of land use and reduction of GHGs have been made; however, the adverse environmental impact of the expansion of the sector has continued to rise (Herrero et al. 2021b). While the sector is part of the overall climate change problem, it must also be part of the solution. Reducing consumption of ASF, particularly of red meat, can potentially benefit the environment. Good resource management practices for soil and water that contribute to promoting sustainable food systems must be rewarded, with *payments for ecosystem services* as an option (Daily and Polasky 2019; Rahman and Hickey 2019). In some countries, there is a need to reduce the over-use of chemical fertilizers that leads to significant environmental pollution and climate change. Boosting nature-based solutions (Jensen et al. 2020) and nature-positive production calls for *transforming soil management, farm input use, agronomy* (Neufeld et al. 2021; Lal 2017), and livestock and aquatic food systems in ways that sustainably boost production to meet current and future food demands, *protecting and using biodiversity through biophysical and ecological practices* (van Zonneveld et al. 2021), rapidly reducing the use of pesticides in intensive crop production, similarly reducing the use of antibiotics and steroids, and protecting the agriculture- and forest-related genetic base (Schmitz et al. 2021). Adopting circularity in the livestock sector can fulfill a significant part of the human protein need and lower the adverse environmental impacts. Alternatives to the current inputs for the livestock sector, including recycled feed and *superfeeds* and feeds from protein sources such as protein rich insects, woody plants, algae and seaweed, need further research and exploration before being expanded at scale (Herrero et al. 2021b; Van Zanten et al. 2019). Of critical importance in this context is the *rapid reduction of the use of antibiotics and steroids in livestock and aquatic food* production systems. Greater emphasis must also be given to the development of green technologies that deploy ecologically suitable trees and indigenous perennial species to boost nature-positive production, and the reduction of large monocultures (Niggli et al. 2021; Snapp et al. 2021). Similarly, *organic fertilizers and bio-stimulants from land and marine sources that can replace chemical fertilizers in promoting soil plant growth* and increasing yields can be further explored (Alae-Carew et al. 2020). *Novel insurance products* and *efficient social protection programs* that include job creation and a variety of nutrition programs, including school-feeding programs, strengthen resilience (Bundy et al. 2018).

Future scientific and technological developments can increase the portfolio of bioproducts developed from local biodiversity, in keeping with a *circular bio-economy* approach (Trigo et al. 2021). Accelerating the reduction of food waste and loss calls for developing *food processing, refrigeration, storage and warehouse technologies* (Dobermann et al. 2021). It also calls for *modifying consumption behaviors, lifestyle choices*, and the perverse incentive to buy much more than needed. A rapid move towards climate-positive and climate-resilient food systems should employ *carbon pricing at appropriately high levels* and incentives for technologies that facilitate adaptation and mitigation (Zilberman et al. 2019; Zarnowiecki et al. 2020). Initiatives for *carbon farming* (growing carbon in soil and trees as a tradable commodity) and related payment schemes should be explored. Climate finance for adaptation has important ecological opportunities in the food system and is also pro-poor. It only currently accounts for a very small proportion of climate finance, and it needs to be increased (Van der Ploeg et al. 2019).

Food systems need to become more prepared for and resilient to not only extreme weather events and climate shocks, but also market and inflationary shocks, health shocks, natural disaster shocks, political/governance shocks, cyber shocks, and other emerging shocks. The characteristics, scale and impact of risks continue to evolve (World Economic Forum 2021), and food-related crises are rising in likelihood and severity. Science also has a growing role in developing a common language to converge multiple knowledge systems and shared goals under emerging risks and uncertainties and how to prepare for and manage them. Rigorous implementation research is needed to strengthen the fit-to-context design and delivery of such programs, and thereby strengthen the resilience of chronically vulnerable communities and their food systems.

### 2.3 Innovations for Overcoming Inefficient and Unfair Land, Credit, Labor, and Natural Resource Use Arrangements, and Facilitating Empowerment of Women, Youths and Indigenous Peoples

Poverty and hunger are interlinked, and reducing extreme poverty directly impacts the elimination of hunger and malnutrition. Among the effective ways to sustainably eradicate poverty and inequality is boosting the opportunities and capacities of the poor and those living in situations of vulnerability, through ensuring more equitable access to resources, i.e., to natural resources and economic assets. *Providing and protecting the land rights* of smallholders – especially female smallholders, and Indigenous Peoples – is critical in this context, as is overcoming exploitative share tenancy. *Inclusive approaches are more possible, affordable and controllable through block chain ledgers of land ownership and credit.*

Ensuring decent work is a key area, and calls for regulation and value chain transparency. The potential for significantly expanding green jobs within food systems must be vigorously pursued. *Pro-poor asset sharing investments and programs that empower poor people to build their asset base* offer promise. Nonetheless, eliminating poverty alone will not make healthy diets affordable for all. Changing food systems need to ensure that people with low incomes can access a healthy diet by *enabling them to earn living wages and have access to social safety nets.*

The roles of **women** are very important for productive, healthy and sustainable food systems (Schmitz et al. 2021). Many food systems are unequal or breed inequalities through land and other asset ownership and market power relationships, whereby power imbalances are a common phenomenon. Besides gender inequalities, overall inequalities across classes, regions, rural-urban contexts, and social groups also influence whether food systems will transform so as to be healthier, more sustainable, and equitable. Women's voices being included in policymaking – as they are cognizant of the needs and wants of women and societal norms and issues – is critical.

The situation of the **young**, as well as the elderly, deserves particular attention. Key innovations include policies for transforming land tenure in equitable ways, providing more and better education investments that enable and empower youths and women and allow them unfettered access to knowledge and information, facilitating job training and education programs, providing affordable financial services, and including youths more fully and meaningfully in policymaking processes. *Vocational training with multi-faceted curricula relevant to rural economic space and food systems need to be scaled up.* Youths have the right and responsibility to learn about food system dynamics and to be fully engaged in opportunities to transform the food systems that they will inherit. The inclusive transformation of smallholder farming will be imperative for youths. Smallholders are not a homogenous group, and transformation of the small farm economies around the world will call for different policies to address the heterogeneity of smallholders.

## *2.4 Bio-science and Related Digital Innovations for People's Health, Food Systems' Productivity and Ecological Well-being*

Specific scientific opportunities for innovations here include *genetic engineering, genome editing, alternative protein (including more plant-based and insect-derived protein) sources* (van Vliet et al. 2020) *and essential micronutrient sources, cell factories, microbiome/soil and plant health technologies, plant nutrition* *technologies* (Jensen et al. 2020), *and animal production and health technologies*. These advances in science and technology have great potential to meet food system challenges such as restoring soil health and functionality (Lal 2017), improving the resource efficiency of cropping systems (Pretty et al. 2018), breeding orphan and underserved crops (Padulosi et al. 2019), and re-carbonizing the terrestrial biosphere. *Modern plant breeding techniques that allow plants to capture nitrogen from the air reduce the need for fertilizers and improve nutritional qualities.*

However, it must not be neglected that there are potential risks associated with science-based innovations that need to be considered within the science systems and through societal dialogues around transparency, ethical standards and reviews, and biosafety measures, and – where needed – through regulatory policies. Adopting the *One Health approach*, i.e., the health of soil, plants, animals, people, ecosystems and planetary processes, being one and indivisible, would be an important contribution (Lal 2020a).

Translating bio-science innovations into reality does not happen automatically: property rights, skills, and data are key for the translation and management of scientific innovations in practice (Webb et al. 2021). However, b*io-sciences increasingly benefit from digital innovations and artificial intelligence* (Benfica et al. 2021). Nonetheless, these technologies sometimes run the risk of exclusion through the creation of monopolies that need to be prevented through anti-trust regulations. Hence, *innovations in governance structures* are needed to ensure that access to bio-science and digital technologies is not hindered. Furthermore, developing these bio-science and digital innovations and ensuring that they – especially the potentially controversial technologies – contribute to sustainability is not sufficient; rather, it will be important to *adapt them to local conditions*, make them accessible and affordable to farmers, especially smallholders, and use them to enhance local and traditional knowledge. It will also be important to have open information-sharing so that users are aware of the opportunities, costs and benefits of new innovations and are able to better use the available technology and implement innovations (Thornton et al. 2019). To ensure that poor communities are not left behind, governments of countries in the global South need to invest in the *creation of capacities and expertise for developing and utilizing bio-sciences and digital technologies, receiving support for that from development partners.* It is important that Indigenous Peoples and local people in general receive the benefits of the innovations that result from their interactions and information-sharing with scientists.

## 2.5 Innovations to Keep and Regenerate Soils, Land, Coastal Areas and Water, Including Oceans, and Protect the Agricultural Genetic Base and Biodiversity

One-third of global land area is degraded (Le et al. 2016). Soil degradation is being exacerbated by climate change, along with land misuse and soil mismanagement (IPCC 2019). Water is becoming increasingly scarce and polluted (Ringler et al.

2021). Ecosystem services of land, forests, and water cycles are being undermined (Mirzabaev et al. 2019). The livestock sector needs particular attention in this regard; it is a major user of land and water and has significant negative impact on the environment. One-third of the global land suitable for crop production is used to produce livestock feed (FAOSTAT 2018). The sector has contributed, and continues to contribute, to global biochemical cycles that cause a loss of biodiversity (Herrero et al. 2021b). Resource protection and enhancement of terrestrial resources must not exclude coastal areas and their links to the oceans. Technology-based innovations are needed to support sustainable soil, agricultural, and water management, protect natural resources from degradation and restore degraded resources, and maintain and even increase biodiversity in agricultural settings (Shukla 2019; Smith et al. 2019). This underlines the need to advance knowledge of plant genetic diversity and microbial diversity, taking local climate variability into account (Guerra et al. 2020). *Harnessing soil microbes to add to depleted soils for the purpose of improving structure, carbon capture and yields is a promising innovation opportunity.* The use of *modern hand-held digital devices for in-field measurement* and *remote sensing measurement of soil carbon* can become a significant opportunity for both climate policy and productive plant nutrient management. These examples highlight the interconnectedness of technological and policy innovations, because the technologies can facilitate the increased feasibility of payments for ecosystem services. Similarly, agro-ecology and other regenerative *practices for resilient landscapes* at scale promise opportunities. They need long-term accompanying science. An integrated approach for sustainable soil management should be considered and incentivized. Locally adapted sustainable intensification of existing agricultural systems, including the livestock sector, is also needed (Bernard and Lux 2017; Pretty et al. 2018; HLPE 2019). In the livestock sector, production of dual-purpose crops, improved feeding practices, agroforestry and pasture intensification have potential for scaling up.

Primary forests are over-exploited, including due to the non-sustainable expansion of agriculture. Conversion of intact ecosystems, including carbon-dense, biodiverse forests for livestock production, is a major environmental concern. *Innovations in agroforestry* with trees and bushes and in landscape contexts can contribute to large-scale productive land use, combined with ecological and climate-positive ecosystem services (Olsson et al. 2019). Wild foods (e.g., berries and fruits) are important for food security and nutrition for both smallholder farmers and Indigenous Peoples (Angelsen et al. 2014). Traditional food and forest systems – including Indigenous Peoples' food systems – need to be better understood and protected when designing policies (Azam-Ali et al. 2021).

### 2.6 *Innovations for Sustainable Fisheries, Aquaculture, and Livestock*

**Science-based innovations for the livestock sector** that ensure the availability and affordability of sustainably produced, high quality protein need support and scaling up. These include the sustainable intensification of livestock systems. Ensuring the availability of key inputs and services, as well as the development of associated value chains and market integration, is a prerequisite for widespread adoption of sustainable practices. Improving livestock productivity can help mitigate the negative environmental impacts and reduce GHG emissions. Replacing currently used animal feed with microbial protein from sewage and *superfeeds* like algae and grass and using organic anti-methanogenic compounds can reduce the cropland area used for the production of feed and decrease methane emissions. GPS devices, robotics and sensors can also be effectively used for controlled grazing, surveillance, and precision feeding. Alternatives to animal-based protein, including insect-based proteins, cultured meat, algae and seaweed, should also be explored. Institutional innovations, including true-cost accounting methods, may be used to discourage the consumption of meat and dairy products in regions where consumption levels are high.

Given the tremendous current and future potential of wild and farmed seafood and seaweed to help assure healthy diets, it is critical to broaden the understanding of food systems to more fully include the aquatic food systems (Leape et al. 2021). The livestock sector poses challenges due to its salience as the key provider of high-quality nutrition (esp. protein) and an income source for farming communities, while being a key contributor of global GHG emissions.

**Institutional innovations are needed to overcome the misuse of oceans as commons:** We are approaching tipping points in regard to harvesting from nature, and unless we *stop treating the oceans as commons that can be exploited* for perpetuity, we will accelerate species extinction, among other irreversible changes. Ecological science perspectives and global cooperation and institutions are needed to bring the harvesting of oceans to sustainable levels and protect biodiversity.

**Science-based innovations for sustainable aquatic foods** that protect and harness oceans and coastal areas can play a growing role in reducing hunger and malnutrition and building healthy, nature-positive and resilient food systems (Costello et al. 2019). Innovations must support aquatic foods "to increase nutritional diversity, reduce waste, address environmental change and management failures, improve livelihoods of fishing and coastal communities, and capitalize on opportunities to sequester carbon in the marine environment." (International Food Policy Research Institute 2020) Of critical importance are innovations in fish-feeding systems: *insect rearing and the use of oil rich modified legumes as fish feed in improved aquaculture to avoid depletion of oceans are potential options. Enhancing the use of organisms of lower trophic levels for human consumption, e.g. micro-algae and seaweed, can lead to their evolution as foods.*

### 2.7 *Engineering and Digital Innovations for Efficiency and Inclusiveness of Food Systems*

Digital innovations and engineering that hold much promise for making food systems more efficient, productive, and sustainable are touching on all components of food systems. Examples include *artificial intelligence, big data analysis, remote sensing and robotics* (Taylor et al. 2021), *mechanization, sub-surface drip irrigation with conservation agriculture, precision agriculture, vertical farming, indoor farming, and digitized food processing* (Lal 2020b). The use of *sensors to monitor the origin and quality of products and ingredients all along the food chains* can reduce losses, guarantee safety and reduce unnecessary "in-transparencies."

The ways in which digital innovations can be put to work to optimize agricultural production processes include using *drones and advanced analysis of image data to identify pests and diseases in real time*. With improved access to biotic (pests and diseases) or physical (meteorological, SAT early warning systems) information and remote sensing, producers can use their mobile phones to strengthen their agricultural practices and make better use of inputs and resources.

Digitization in the food system does not necessarily enhance equity, and it may even benefit large-scale farming and processing at the expense of smallholder farming. Thus, appropriate *governance structures* are needed to ensure that access to digital technologies is not hindered and that data collected from smallholders are appropriately protected so that smallholders are not "data-exploited." Inequitable access to digital technologies could significantly impede the transition to equitable food systems. Easing information access for women is particularly important. Strengthening the *e-commerce ecosystem* could transform rural livelihoods, providing *platforms* to reach the last-mile households and better connect them to the wider economy.

The growing role of *digital innovations in science and technology processes* that serve bio-chemical sciences and engineering of relevance for food systems is also noteworthy.

It is of note that digitization itself facilitates decentralized organization of science and research that produces technological, policy and institutional innovations that are context-specific, and thereby offers extraordinary new opportunities to re-organize how science is undertaken, delivered, and used in participatory ways.

Further development to make digital technologies affordable and accessible for small- and medium-sized farmers is essential to avoid even further reducing their competitiveness (Malabo Montpellier Panel 2019). In this context, revisiting and reinvigorating *agricultural extension services with digital options* is called for. Attention to employment effects is also called for, as well as attention to ethical considerations of data use and data ownership. Investments are also needed to scale up universal access to digital technologies and key infrastructure, in particular, access to rural electrification, wherever possible based on renewable energy sources.

## 3 Modeling Synergies and Trade-Offs Between Actions in Food Systems

The sets of innovations and actions mentioned above are connected, and there are synergies and trade-offs among them. Understanding these synergies and trade-offs is critical to maximizing the effectiveness of innovations and actions. A convincing game-changing action in one food systems domain may cause adverse effects in another. For example, a fertilizer subsidy that increases income and reduces hunger may have an adverse environmental effect if this leads to excessive nitrogen use. To avoid such unintended consequences, food system modeling is essential.

Furthermore, food systems do not operate in isolation. Innovations go beyond food systems and are connected to transformations in health systems ("One Health"), energy and environmental systems (climate), economic systems (trade), and evolving science and knowledge systems. Strengthening the interactions among scientists specializing in food systems, health, climate, and energy will make it possible to generate the required expertise. Furthermore, researchers and users of research need to work together to increase the chances of achieving food systems-related SDGs. Supporting local innovations and creating knowledge, participatory science, and living labs should be explored at scale.

A recent review of the advanced quantitative global modeling (Valin et al. 2021) found **strong synergies between SDG2 and other related SDGs**. These synergies and trade-offs are illustrated in Fig. 1. In particular, SDG1 (no poverty) is central for food security and can unlock many additional benefits across the SDGs. SDG2 is closely integrated with SDG3 (good health and well-being) due to the close link between malnutrition and maternal and child health, as well as deaths associated with poor diet. Other socioeconomic SDGs – including SDG4 (education), SDG5 (gender equality), SDG8 (decent work and economic growth), SDG10 (reduced inequality), SDG11 (sustainable cities and communities), SDG16 (peace, justice and strong institutions), and SDG17 (partnership) – are key enablers for SDG2. These potential synergies merit greater attention in regard to accelerating food system transformation.

The importance of trade-offs must also be recognized. Agricultural production substantially contributes to global warming, nutrient pollution, the degradation of water quantity and quality, biodiversity loss, and soil degradation. Climate action (SDG13) requires curtailing greenhouse gas-intensive products (meat, dairy, rice). Achieving biodiversity on land (SDG15) requires limiting deforestation associated with agriculture expansion and establishing new conservation areas. Achieving environmental water flows (SDG6) requires reducing water withdrawal for irrigation. Quantitative assessments show more efficient production systems and technologies and the pricing of externalities. Additionally, integrated resource management can mitigate some of these trade-offs, although it is unlikely to succeed in addressing them altogether.

Forward-looking analyses indicate that, to achieve the SDG2 targets and other goals, deeper transformation of food systems at the global level will be required,

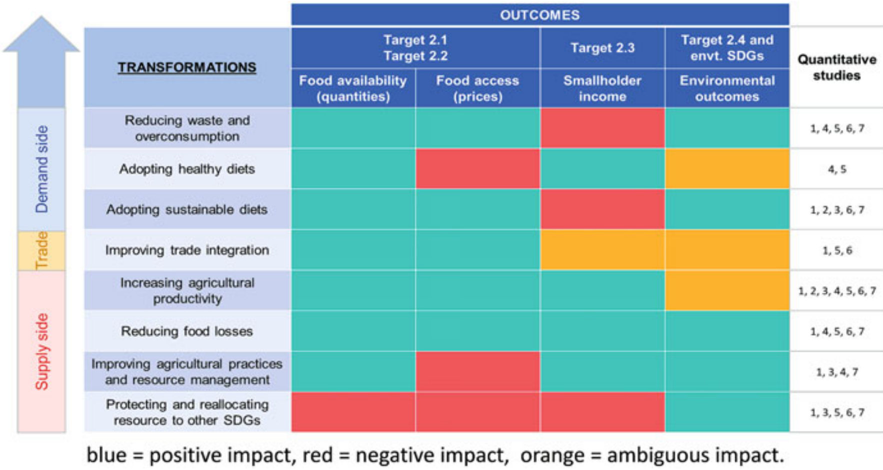


**Fig. 1** Key transformations implemented in global analyses and their typical impact for relevant indicators (Valin et al. 2021)

combining supply- and demand-side measures. Such transformation entails new supply-side investments, effective trade and markets, and modified consumer behavior, with a fast transition towards more sustainable and healthy diets and sharp reductions in food loss and food waste. SDG12 (responsible production and consumption) is a key goal for the successful transformation of global food systems to achieve SDG2.

With an integrated modeling framework, Laborde and Torero (this volume) model six individual interventions similar to those presented in Fig. 1 with respect to their impact on food systems, the prevalence of undernutrition, ecological effects in terms of GHG emissions, land and energy use, and the use of chemical inputs. Given the synergies and complementarities between these scenarios, the authors assess them as a package. The sensitivity to the results is also assessed under different governance principles, such as land use policies.

The scenarios are listed in Laborde and Torero (this volume) and organized around three main pillars: achievement of a more *efficient* and *inclusive* system, allowing consumers and producers to make *better choices*. The results of the different scenarios are consistent with the baseline of *The State of Food Security and Nutrition in the World 2020*, namely that, in 2019, there were 690 million undernourished people in the world and healthy diets were unaffordable for almost three billion people. The findings confirm that ending chronic hunger at a 5% level is feasible by 2030 with the appropriate balance of interventions. While no intervention alone could solve the problem, key interventions to increase the efficiency of food systems – through increased *farm productivity* and a reduction of *food loss and waste* – will reduce the number of people in chronic hunger by 314 million by 2030.

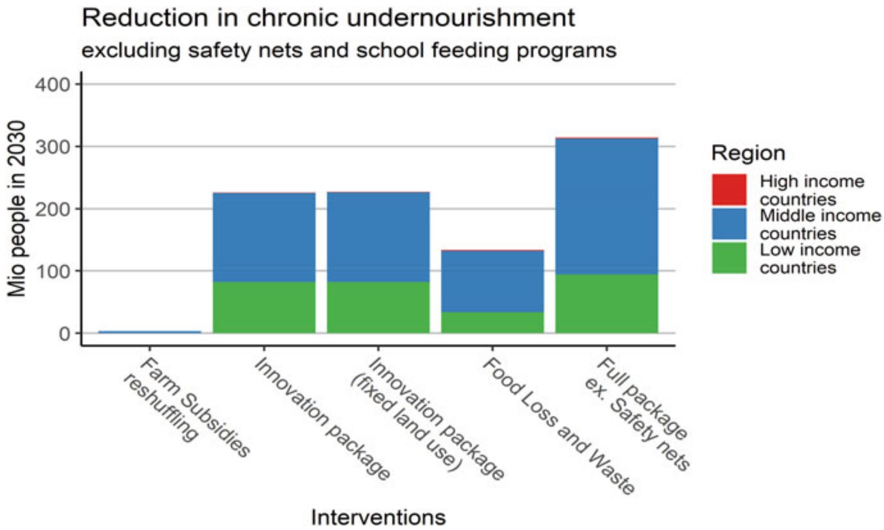


**Fig. 2** Number of people (mio) removed from a state of chronic undernourishment in 2030. (Source: Preliminary results based on Laborde and Torero, 2021)

Beyond hunger, 568 million people will be able to afford healthy diets. To target the remaining population, *safety nets* and targeted programs like *school-feeding* interventions are required. When adding such safety nets into the model, it is possible to cover the 2.4 billion remaining people without access to healthy diets (Fig. 2).

Achieving the end of widespread hunger requires significant *resource mobilization*, representing 8% of the size of food markets.[4] The actions – referred to as "better choices," including *consumer incentives* and *farm subsidy re-purposing* – do not contribute to the total costs, because they are designed to be cost-neutral for the government and producers (farm subsidies), as well as consumers (food tax/subsidies), in each country. The cost structure is dominated by the large investment in innovations for productivity, in people, who impact the value chains and national economies (45%), and in the social safety nets (36%).

Clearly, the two main items are different, since the latter involves recurrent spending every year and will have to be managed and financed by governments alone. Since the needs are unevenly distributed globally, a significant solidarity effort is required for global coordination, especially to support the transformation of food systems in low-income countries.

As previously shown, no single intervention can end malnourishment. The actions modeled will generate trade-offs in greenhouse gas emissions (emissions from agricultural production and net emissions from agriculture, forestry, and other

[4] 2030 spending and food market values, as estimated by the model to guarantee full consistency.

land use, or AFOLU), chemical inputs (increased use of chemical inputs per hectare), biodiversity (reduction of forest habitat and agricultural land) and energy consumption.

The effects indicate environmental improvement as a consequence of reducing food loss and waste. However, when it comes to net agricultural emissions and AFOLU, the effect is negative, as is the case for forest land. This highlights the need for policies that can stimulate investments in innovation for carbon farming – growing carbon in soil and trees as a tradable commodity – and related payment schemes for ecosystem services, as indicated in Sect. 2.5 concerning the science and innovation actions above.

## 4 Enabling Food System Transformation

Transformation of food systems that are under way do not guarantee that the food-related SDGs – especially SDG2 – will be achieved. There are fundamental conditions that are essential to enable and leverage food system transformation to achieve the desired objectives, including *facilitating peace and security and conflict resolution, full inclusion of marginalized and vulnerable populations, gender equity, sound governance at all levels, from community to local to regional to national and international,* and *supportive global and national policies for public goods* (Global Panel on Agriculture and Food Systems for Nutrition 2020; International Food Policy Research Institute (IFPRI) 2020). We highlight below the required additional actions in the follow-up to the UNFSS 2021 in the fields of finance, capacity, and governance.

**Finance** Enabling food system transformations requires constant investment in science that has the potential to produce positive change in systems. In 2018, the world science "output" in terms of peer-reviewed publications was 4.04 million, and of these, 14% were related to agricultural and biological sciences (about 298,000) and environmental sciences (about 273,000).[5] Thousands of potentially game-changing insights are generated by the world's scientific communities every year. More attention is needed to identify actionable insights for innovations, and that requires strengthening capacity and innovative financing.

Science systems have been decimated in many countries, especially in the global South. To tap the potentials of science, the public funding of food system science and related research partnerships needs to expand. Governments need to change their low levels of spending on food system-related research and innovation. We call on governments – especially in the global South – to review the level of their investments in food system science and allocate at least 1% of their food system-related GDP to food system science and innovation with a perspective to substantially

[5] Scimago journal and country rankings for 2018.

exceed this target. LDCs should be assisted in quickly reaching the equivalent of this target. About 20 years ago, African ministers responsible for science and technology had already committed to increase public expenditures on research and development to at least 1% of GDP per annum.[6] As basic sciences – for instance, *bio-chemical and nutrition and health sciences* – are becoming increasingly relevant for food systems, the investment in these must also be accelerated and systems for sharing the sciences related to food systems expanded (Beintema et al. 2020; von Braun 2020). There are important new opportunities for engaging private sector science to address public goods in food system innovations, particularly in partnership with the public sector (Herrero et al. 2020). The private sector here is a broad concept, ranging from semi-subsistence farmers to large corporations. It is often overlooked that the former are also proven innovators (Tambo and Wünscher 2017). The knowledge of Indigenous Peoples is another important component of local food systems' innovation landscape. Intellectual property rights protection issues require revisiting so as to align them with sustainability expectations, especially for scientific opportunities that address overcoming hunger and malnutrition (Zilberman et al. 2019; Zarnowiecki et al. 2020). New institutional arrangements may be discussed for sharing intellectual property that could directly reduce hunger and address sustainability concerns.

The follow-up to the Food Systems Summit needs to consider how the investments in the identified priority actions may be financed, and that is where innovative finance approaches that economics research can explore shall be considered. Research suggests that mobilizing the necessary financial resources may include a combination of actions, such as (1) provision of additional – actually double the current amount – international development funds (ODA) for agricultural and rural development, food and nutrition security; (2) reallocation of agricultural subsidies towards investment in sustainable development and the scaling up and redesigning of social safety nets; (3) initiation of a new dedicated "end hunger" fund, perhaps through expanded IDA; and (4) possibly the financing of innovative financial mechanisms such as "End Hunger Bonds" through support from incremental special drawing rights (SDRs) (von Braun et al. 2021b; Díaz-Bonilla 2021). The private sector should be part of this resource mobilization, expecting long-term returns from a more prosperous society. Research shall identify what combinations of finance may contribute to the sustainable financing of food system transformation.

**Capacity** Of particular importance are investments in *improving data, methods, models and tools for all food system components* and actors, as well as building or *enhancing (shared) research infrastructures related to (research) data, modeling platforms, observation and monitoring networks* to support the required advances in research and innovation, especially in the global South (Inter-Academy Partnership 2018). Integrated *global food system models* are needed, as existing models do not have consistent global coverage and are not designed to assess the impacts of all

[6] Declaration of the first NEPAD Ministerial conference on Science and Technology, 7 November 2003, Johannesburg, South Africa https://sarpn.org/documents/d0000614/index.php

elements of food systems (Webb et al. 2020b). Besides global foresight work, strengthening national and – where possible – subnational/local policy scenarios and foresight work is also necessary. More attention needs to be paid to strengthening local research capacities, *expanding research collaboration among public and private sector research and indigenous systems*, sharing research infrastructure and data, developing more inclusive and equitable science partnerships and follow-up mechanisms, systematically learning what works and what can be scaled up and translating that knowledge into action, improving the efficiency in the way knowledge is generated and shared, and *addressing intellectual property rights issues when they hinder innovations* that can serve food and nutrition security, food safety, and sustainability goals (Hendriks et al. 2021b). With the increased recognition of their central role in achieving many development goals, food systems will be expected to perform a more complex set of activities, and this requires new and more appropriate holistic metrics. Protection of the freedom of science to innovate and experiment while adhering to ethical standards needs to be continually reinforced.

Because significant components of food systems are local, the Summit has to ensure that its outcomes and deliverables turn into positive local actions. This requires science to align with national and local agendas for the implementation actions. The proximity of science to decision-making is important to connect the timeliness and relevance of science to policy where and when it is needed. Similarly, the development of national and local infrastructure and expertise to effectively link science to decision-making is important. The science underpinning food system transformation becomes more inter- and trans-disciplinary, more open to a wide range of innovations and their diverse stakeholders, and more appropriately configured and scaled to different contexts. Relatedly, it would be important to innovate and *improve the methods for analyzing the performance of food systems* (e.g., analyzing their impact on health, nutrition and sustainability goals) at different levels (local, national, global).

Transformation is not possible without science, and in many instances, citizen participation in research and implementation can be very supportive for the transformation of farming, the application of new technologies, the shift to healthy diets, and other key elements of successful food system transformation. Citizen science has an important role to play in inclusive food system transformation, especially with farmers as co-designers directly participating in the development of innovations and with scientists being more open to and collaborating on fair terms with start-ups. Indigenous Peoples knowledge systems should be partnered with in such approaches.

The international sharing of science and the participation of science in the follow-up to the Food Systems Summit as part of implementation agendas is vital. Proposals for international collaboration include supporting low- and middle-income countries in building and sustaining capacities to acquire and deploy technologies through joint research, education and training programs. Beyond investing in capacities to undertake research, it will be important to also invest in capacities to act upon research: in other words, to put to effective use the knowledge and innovations that already exist (e.g., traditional and indigenous knowledge) or that are generated from new research. This calls for investing in *strengthening the skills of all food system actors*, especially in emerging economies, where these skills tend to be more limited. In many instances, what is lacking is actionable knowledge that may contribute to systemic changes, which requires supporting local innovations and encouraging and facilitating the co-creation/co-design of knowledge. In support of this, *leading research organizations from world regions could form networks (or alliances)* to share science and develop actionable knowledge that supports food system transformations.

**Governance and Science-Policy Interface** In contrast to other subjects of global concern that were agreed upon at the Earth Summit in Rio in 1992, agriculture, food security and nutrition do not have an international agreement or convention to consolidate actions. Climate, biodiversity and desertification have their dedicated conventions and ensuing subsidiary bodies, secretariats and further protocols. Fueled by regular meetings of the conference of parties and underpinned by a solid science-policy interface, they have made enormous progress. Thus, we believe that the time has come to consider such a set of agreements and mechanisms for the complex area of food systems, obviously fully recognizing existing efforts and agents. The UNFSS may wish to consider opening a process for *exploring a treaty on food systems*. In a related manner, food system science and policy need a stronger scientific framework for constructive and evidence-based interaction that will allow it, too, to move ahead for the long term (von Braun 2018). At the national level, coherent national food systems research policies need to be better integrated into national development policies, such that countries develop their own context-specific food systems policies and strategies. At the international level, some have proposed strengthening the contribution of science to policymaking for transformational food systems with an Intergovernmental Scientific Advisory Panel, while others advocate strengthening and better connecting existing mechanisms (Hendriks et al. 2021a; Inter-Academy Partnership 2018; von Braun and Kalkuhl 2015). We suggest exploring options for an inclusive, global science-policy interface (SPI) for a sustainable food system that connects national and global food systems concerns and will assist in an evidence-based follow-up to the proposed Summit actions and for the long term. This proposition is based on three considerations: (1) the growing complexity of food value chains from resource use to human nutrition and their increasing globalization, which urgently requires a new integrated approach that draws on all related science for sustainable agriculture, food and nutrition systems; (2) the absence of a comprehensive and timely system to collect, analyze and assess data on the diagnosis and technical, economic and social solutions for creating long-term sustainable, affordable, nutritious and safe food systems; and (3) the limited or non-existent translation and traceability of scientific data and experiences into evidence-based policy that precludes the application of experiences across countries and regions (Hendriks et al. 2021c; Hodson de Jaramillo et al. 2021; Moughan et al. 2021; Fan et al. 2021; Serova et al. 2021; Gulati et al. 2021). Addressing these considerations requires a global mechanism that mobilizes the leading food systems scientists worldwide and across disciplines to support the SPI through co-production, open access, and communication of knowledge. The effective and independent participation of research communities from low-income countries and emerging economies in the SPI must be strengthened to enhance credibility, relevance and legitimacy. We call upon governments and UN agencies to *initiate a process to explore options – those already existing*[7] *as well as new – for a global SPI* for a sustainable food system. As such, this would be a concrete outcome of the UNFSS.

Science and policy have a lot to gain from cooperation, but the independence of science to address policy and institutional opportunities and failures with evidence-based insights must not be compromised. Nonetheless, science that produces new insights also needs to constantly earn the trust of society, and in view of the cultural sensitivity of all matters related to food, policies and rules must assure confidence in scientific endeavors. Anti-science sentiments exist in parts of society. While pursuing new insights and truths, there are many issues upon which scientists themselves do not agree, which sometimes irritates policymakers and practitioners. Adhering to responsible and ethical principles, science must collaborate with a broad range of stakeholders. The improved quality and timeliness of science translation and communication for policymakers and non-technical audiences are helpful, along with attention to ethics, peer review, scientific integrity and excellence, transparency and declarations of interest in science.

In closing, science, innovation, and technologies play critical roles among the measures to achieve food system transformations. All sciences – natural sciences and social sciences, basic sciences and applied sciences – in collaboration with diverse traditional knowledge systems must deliver innovations and make significant contributions for the necessary food system transformation in order to achieve the SDGs, especially SDG2, and the complete 2030 Agenda.

**Acknowledgments** The authors developed this chapter in close collaboration with the Scientific Group of the UN Food Systems Summit, which has engaged extensively with scientific communities around the world, including the partners and contributors of more than 40 reports and briefs prepared specifically for the Scientific Group's evidence-based contributions to the Summit. The authors thank the participants of Science Days in 2021 for their thoughtful input and comments on the draft paper, as well as all others who shared comments and suggestions.

[7] Including the CGIAR (https://www.cgiar.org/), the Global Forum on Agricultural Research and Innovation (GFAR) https://www.gfar.net/), the High Level Panel of Experts on Food Security and Nutrition (HLPE) (http://www.fao.org/cfs/cfs-hlpe), and the InterAcademy Partnership (IAP) (https://www.interacademies.org/).

## References

Alae-Carew C, Nicoleau S, Bird FA, Hawkins P, Tuomisto HL, Haines A et al (2020) The impact of environmental changes on the yield and nutritional quality of fruits, nuts and seeds: a systematic review. Environ Res Lett 15(2):023002. https://doi.org/10.1088/1748-9326/ab5cc0

Allen S, Badiane O, Sene L, Ulimwengu J (2014) Government expenditures, health outcomes, and marginal productivity of agricultural inputs: the case of Tanzania. J Agric Econ 65(3):637–661

Angelsen A, Jagger P, Babigumira R, Belcher B, Hogarth NJ, Bauch S et al (2014) Environmental income and rural livelihoods: a global-comparative analysis. World Dev 64:S12–S28. https://doi.org/10.1016/j.worlddev.2014.03.006

Azam-Ali S, Ahmadzai H, Choudhury D, Goh EV, Jahanshiri E, Mabhaudhi T et al (2021) Marginal areas and indigenous people–priorities for research and action. In: Food systems summit brief prepared by Partners of the Scientific Group. https://doi.org/10.48565/fd4f-rk35

Barakat S, Milton S (2020) Localisation across the humanitarian-development-peace nexus. J Peacebuild Dev 15:2. https://doi.org/10.1177/1542316620922805

Beintema N, Pratt AN, Stads G-J (2020) Key trends in global agricultural research investment. ASTI Program Note. https://www.asti.cgiar.org/sites/default/files/pdf/Global-update-ASTI-note.pdf

Benfica R, Chambers J, Koo J, Nin-Pratt A, Falck-Zepeda J, Stads GJ, Arndt C (2021) Food system innovations and digital technologies to Foster productivity growth and rural transformation. In: Food systems summit brief prepared by Research Partners of the Scientific Group. https://doi.org/10.48565/scfss2021-6180

Bernard B, Lux A (2017) How to feed the world sustainably: an overview of the discourse on agroecology and sustainable intensification. Reg Environ Chang 17:1279–1290. https://doi.org/10.1007/s10113-016-1027-y

Bhutta ZA, Das JK, Rizvi A, Gaffey MF, Walker N, Horton S, Webb P, Lartey A, Black RE (2013) Evidence-based interventions for improvement of maternal and child nutrition: what can be done and at what cost? The Lancet 382(9890):452–447

Bron GM, Siebenga JJ, Fresco LO (2021) In the age of pandemics, connecting food systems and health: a global one health approach. In: Food systems summit brief by partners of scientific group. https://doi.org/10.48565/scfss2021-z850

Bundy D, Horton S, Jamison D, Patton G, de Silva N (eds) (2018) Re-imagining school feeding: a high return Investment in Human Capital and Local Economies. DCP3 and WFP. http://www.dcp-3.org/schoolfeeding

Center for Development Research (ZEF) of the University of Bonn in cooperation with the Food and Agriculture Organization of the United Nations (FAO) (2020) Investment costs and policy action opportunities for reaching a world without hunger (SDG 2). http://www.fao.org/documents/card/en/c/cb1497en

Costello C, Cao L, Gelcich S et al (2019) The future of food from the sea. In: Capture fisheries: current status and trends. World Resources Institute, Washington, DC. Available online at www.oceanpanel.org/future-food-sea

Daily GC, Polasky S (2019) How do we stem biodiversity loss? In: Biological extinction: new perspectives. Cambridge University Press, pp 332–357. https://doi.org/10.1017/9781108668675.015

Diao X, Reardon T, Kennedy A, DeFries RS, Koo J, Minten B, Takeshima H, Thornton P (2021) The future of small farms: innovations for inclusive transformation. In: Food systems summit brief by Partners of Scientific Group. https://sc-fss2021.org/wp-content/uploads/2021/06/FSS_Brief_Small_Farms.pdf

Díaz-Bonilla E (2021) Financing SGD2 and ending hunger. In: Food systems summit brief prepared by Research Partners of the Scientific Group for the Food Systems Summit. https://doi.org/10.48565/scfss2021-ba75

Dobermann A, Bruulsema T, Cakmak I, Gerard B, Majumdar K, McLaughlin M, Reidsma P, Vanlauwe B, Wollenberg L, Zhang F, Zhang X (2021) A new paradigm for plant nutrition. In: Food systems summit brief prepared by research Partners of the Scientific Group. https://doi.org/10.48565/SCFSS2021-HG55
Downs S, Demmler KM (2020) Food environment interventions targeting children and adolescents: a scoping review. Glob Food Sec 27:100403. https://doi.org/10.1016/j.gfs.2020.100403
Dury S, Bendjebbar P, Hainzelin E, Giordano T, Bricas N (2019) Food systems at risk. New trends and challenges. FAO-CIRAD-European Commission, 132 p, ISBN 978-2-87614-751-5, Rome. https://doi.org/10.19182/agritrop/00080
Fan S, Huang J, Zhang F, Zhao W, Song H, Nie F . . ., Cong W (2021) Transforming Chinese food systems for both human and planetary health. https://doi.org/10.48565/scfss2021-vq06
FAO (2018) The future of food and agriculture – alternative pathways to 2050. Summary version, Rome, 60 pp. http://www.fao.org/3/CA1553EN/ca1553en.pdf
FAO, IFAD, UNICEF, WFP, WHO (2021) The state of food security and nutrition in the world 2021. FAO, Rome. http://www.fao.org/3/cb4474en/online/cb4474en.html
FAOSTAT (2018) FAOSTAT food balance sheets. Available at: http://www.fao.org/faostat/en/#data/FBS. Accessed 16 June 2021
Fears R, Canales C (2021) The role of science, technology and innovation for transforming food systems globally. In: Food systems summit brief by Partners of Scientific Group. https://doi.org/10.48565/scfss2021-q703
Food and Land use Coalition (2019) https://www.foodandlandusecoalition.org/wp-content/uploads/2019/09/FOLU-GrowingBetter-GlobalReport.pdf
Global Panel on Agriculture and Food Systems for Nutrition (2020) Future food systems: for people, our planet, and prosperity. https://www.glopan.org/foresight2/
Guerra CA, Heintz-Buschart A, Sikorski J et al (2020) Blind spots in global soil biodiversity and ecosystem function research. Nat Commun 11:3870. https://doi.org/10.1038/s41467-020-17688-2
Gulati A, Paroda R, Sanjiv P, Narain D, Ghanwat A (2021) Food system in India: challenges, performance and promise. In: Food systems summit brief prepared by research Partners of the Scientific Group for the food systems summit. https://doi.org/10.48565/scfss2021-b823
Hainzelin E, Caron P, Place F, Dury S, Echeverria R, Harding A (2021) How could science-policy interfaces boost food system transformation? In: Food systems summit brief by Partners of Scientific Group. https://doi.org/10.48565/scfss2021-4y32
Hansen J, Hellin J, Rosenstock T, Fisher E, Cairns J, Stirling C et al (2019) Climate risk management and rural poverty reduction. Agric Syst 172:28–46. https://doi.org/10.1016/j.agsy.2018.01.019
Harris J, Piters BDS, McMullin S, Bajwa B, de Jager I, Brouwer DI (2021) Fruits and vegetables for healthy diets: priorities for food system research and action. In: Food systems summit brief by Partners of Scientific Group. https://doi.org/10.48565/scfss2021-ys30
Headey DD, Alderman HH (2019) The relative caloric prices of healthy and unhealthy foods differ systematically across income levels and continents. J Nutr *149*(11):2022–2033. https://doi.org/10.1093/jn/nxz158
Hendriks S, Soussana J.-F, Cole M, Kambugu A, Zilberman D (2021a) Ensuring access to safe and nutritious food for all through transformation of food systems paper on action track 1. https://doi.org/10.48565/scfss2021-wg92
Hendriks S, de Groot Ruiz A, Acosta MH, Baumers H, Galgani P, Mason-D'Croz P, Godde C, Waha K et al (2021b) The true cost and true price of food. In: Scientific group report for the Food Systems Summit. https://sc-fss2021.org/wp-content/uploads/2021/06/UNFSS_true_cost_of_food.pdf
Hendriks SL, Bekele E, Chaibi T, Hassan M, Miano DW, Muyonga JH (2021c) The role of science, technology, and innovation for transforming food systems in Africa. https://doi.org/10.48565/scfss2021-a948
Herrero M et al (2016) Greenhouse gas mitigation potentials in the livestock sector. Nat Clim Chang 6(5):452–461. https://doi.org/10.1038/nclimate2925

Herrero M, Thornton PK, Mason-D'Croz D et al (2020) Innovation can accelerate the transition towards a sustainable food system. Nat Food 1:266–272. https://doi.org/10.1038/s43016-020-0074-1

Herrero M, Hugas M, Lele U, Wira A, Torero M (2021a) Shift to healthy and sustainable consumption patterns. Scientific group report for the food systems summit: a paper on action track 2. In: The scientific group for the UN food system summit 2021. https://doi.org/10.48565/scfss2021-9240

Herrero M, Mason-D'Croz D, Thornton PK, Fanzo J, Rushton J, Godde C, Bellows A, de Groot A, Palmer J, Chang J, van Zanten H, Wieland B, DeClerck F, Nordhagen S, Gill M (2021b) Livestock and sustainable food systems: status, trends, and priority actions. In: Food systems summit brief by Partners of the Scientific Group for the food systems summit. https://doi.org/10.48565/bonndoc-1

Hertel TW, Elouafi I, Frank E, Morakot T (2021) Building resilience to vulnerabilities, shocks and stresses: a paper on action track 5. In: The scientific group for the UN food system summit. https://doi.org/10.48565/scfss2021-cz84

Hidrobo M, Hoddinott J, Kumar N, Olivier M (2018) Social protection, food security, and asset formation. World Dev 101:88–103

Hirvonen K, Bai Y, Headey D, Masters WA (2020) Affordability of the EAT–lancet reference diet: a global analysis. Lancet Glob Health 8(1):e59–e66. https://doi.org/10.1016/S2214-109X(19)30447-4

HLPE (2017) Nutrition and food systems. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome 152 p. http://www.fao.org/3/a-i7846e.pdf

HLPE (2019) Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. http://www.fao.org/3/ca5602en/ca5602en.pdf

Hodson de Jaramillo E, Trigo EJ, Campos R (2021) The role of science, technology and innovation for transforming food systems in Latin America and the Caribbean. https://doi.org/10.48565/scfss2021-6w45

Hodson E, Urs N, Kaoru K, Lal R, Sadoff C (2021) Boost nature positive production: a paper on action track 3. In: The scientific group for the UN food system summit 2021. https://doi.org/10.48565/scfss2021-q794

Inter-Academy Partnership (2018) Opportunities for future research and innovation on food and nutrition security and agriculture. The Inter-Academy Partnership's Global Perspective. https://www.interacademies.org/sites/default/files/publication/iap_fnsa_global_web_complete_28nov.pdf

International Food Policy Research Institute (2020) 2020 global food policy report: building inclusive food systems. International Food Policy Research Institute. - Reshaping Food Systems, Washington, DC. https://doi.org/10.2499/9780896293670

International Food Policy Research Institute (IFPRI) (2020) Global food policy report: building inclusive food systems. https://doi.org/10.2499/9780896293670

IPBES (2019) In: Brondizio ES, Settele J, Díaz S, Ngo HT (eds) Global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services. IPBES Secretariat, Bonn

IPCC (2019) Summary for policymakers. In: Shukla PR et al (eds) Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/site/assets/uploads/sites/4/2020/02/SPM_Updated-Jan20.pdf

Jensen ES, Carlsson G, Hauggaard-Nielsen H (2020) Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: a global-scale analysis. Agron Sustain Dev 40(1):5. https://doi.org/10.1007/s13593-020-0607-x

Kau A, Ahern P, Griffin N et al (2011) Human nutrition, the gut microbiome and the immune system. Nature 474:327–336. https://doi.org/10.1038/nature10213

Kemmerling B, Schetter C, Wirkus L (2021) Addressing food crises in violent conflicts. In: Systems summit brief by Partners of Scientific Group. https://doi.org/10.48565/scfss2021-h009

Klassen S, Murphy S (2020) Equity as both a means and an end: lessons for resilient food systems from COVID-19. World Dev 136:105104. https://doi.org/10.1016/j.worlddev.2020.105104

Lal R (2017) Improving soil health and human protein nutrition by pulses-based cropping systems. Adv Agron 145:167–204. https://doi.org/10.1016/bs.agron.2017.05.003

Lal R (2020a) Managing organic matter content for restoring health and ecosystem Services of Soils of India. J Indian Soc Soil Sci 68(1):1–15. https://doi.org/10.5958/0974-0228.2020.00001.8

Lal R (2020b) Home gardening and urban agriculture for advancing food and nutritional security in response to the COVID-19 pandemic. Food Secur 12:871–876. https://doi.org/10.1007/s12571-020-01058-3

Le QB, Nkonya E, Mirzabaev A (2016) Biomass productivity-based mapping of global land degradation hotspots. In: Nkonya E, Mirzabaev A, von Braun J (eds) Economics of land degradation and improvement – a global assessment for sustainable development. Springer, Cham. https://doi.org/10.1007/978-3-319-19168-3_4

Leape J, Micheli F, Tigchelaar M, Allison EH, Basurto X, Bennett A, Bush SR, Cao L et al (2021) The vital roles of blue foods in the global food system, – protect and develop the potential of blue foods to help end malnutrition. In: Food systems summit brief prepared by Partners of the Scientific Group. https://doi.org/10.48565/scfss2021-bg71

Malabo Montpellier Panel (2019) Byte by byte: policy innovation for transforming Africa's food system with digital technologies, Dakar, June 2019. https://doi.org/10.2499/9780896296848

Masters WA, Martinez EM, Greb F, Herforth A, Hendriks S (2021) Cost and affordability of preparing a basic meal around the world. In: Food systems summit brief by Partners of Scientific Group. https://sc-fss2021.org/wp-content/uploads/2021/06/FSS_Brief_Cost_of_Basic_Meals.pdf

Miller V, Yusuf S, Chow CK, Dehghan M, Corsi DJ, Lock K, Popkin B, Rangarajan S, Khatib R, Lear SA, Mony P, Kaur M, Mohan V, Vijayakumar K, Gupta R, Kruger A, Tsolekile L, Mohammadifard N, Rahman O et al (2016) Availability, affordability, and consumption of fruits and vegetables in 18 countries across income levels: findings from the prospective urban rural epidemiology (pure) study. Lancet Glob Health 4(10):e695–e703. https://doi.org/10.1016/S2214-109X(16)30186-3

Mirzabaev A et al (2019) Desertification. In: Shukla PR et al (eds) Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/site/assets/uploads/sites/4/2019/11/06_Chapter-3.pdf

Mirzabaev A, Olsson L, Kerr RB, Pradhan P, Guadalupe M, Ferre R, Lotze-Campen H (2021) Climate change and food systems. In: Food systems summit brief by Partners of Scientific Group. https://sc-fss2021.org/wp-content/uploads/2021/05/FSS_Brief_Climate_Change_and_Food_Systems.pdf

Moughan PJ, Chamovitz DA, Ayyappan S, Tanticharoen M, Lal K, Kim YH (2021) The role of science, technology, and innovation for transforming food systems in Asia. https://doi.org/10.48565/scfss2021-tf41

Moustier P, Holdsworth M, Seck PA, Renting H, Caron P, Bricas N (2021) Priorities for inclusive urban food system transformations in the Global South. In: Food systems summit brief by Partners of Scientific Group. https://doi.org/10.48565/3xdb-qq20

Mushtaq S, Kath J, Stone R et al (2020) Creating positive synergies between risk management and transfer to accelerate food system climate resilience. Clim Chang 161:465–478. https://doi.org/10.1007/s10584-020-02679-5

Neufeld LM, Jikun H, Ousmane B, Patrick C, Forsse LS (2021) Advance equitable livelihoods: a paper on action track 4. In: The scientific group for the UN food system summit 2021. https://doi.org/10.48565/scfss2021-tw373

Niggli U, Sonnevelt M, Kummer S (2021) Pathways to advance agroecology for a successful transformation to sustainable food systems. In: Food systems summit brief prepared by research Partners of the Scientific Group. https://doi.org/10.48565/scfss2021-wf70

Olsson L et al (2019) Land degradation. In: Shukla PR et al (eds) Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/site/assets/uploads/sites/4/2019/11/07_Chapter-4.pdf

Osendarp S, Akuoku J, Black R, Headey D, Ruel M, Scott N et al (2020) The potential impacts of the COVID-19 crisis on maternal and child undernutrition in low- and middle-income countries. Preprint under consideration at a Nat Portfolio J. https://doi.org/10.21203/rs.3.rs-123716/v1

Padulosi S, Roy P, Rosado-May FJ (2019) Supporting nutrition sensitive agriculture through neglected and underutilized species - operational framework. Bioversity International and IFAD, Rome, 39 pp

Pretty J, Benton TG, Bharucha ZP et al (2018) Global assessment of agricultural system redesign for sustainable intensification. Nat Sustain 1:441–446. https://doi.org/10.1038/s41893-018-0114-0

Rahman HM, Hickey GM (2019) What does autonomous adaptation to climate change have to teach public policy and planning about avoiding the risks of maladaptation in Bangladesh? Front Environ Sci 7:2. https://doi.org/10.3389/fenvs.2019.00002

Ringler C, Agbonlahor M, Baye K, Barron J, Hafeez M, Lundqvist J et al (2021) Water for food systems and nutrition. In: Food systems summit brief prepared by research Partners of the Scientific Group. https://doi.org/10.48565/scfss2021-tg56

Ruel MT, Alderman H, Maternal and Child Nutrition Study Group (2013) Nutrition-sensitive interventions and programmes: how can they help to accelerate progress in improving maternal and child nutrition? Lancet 382(9891):536–551

Schmitz S, Barrios R, Dempewolf H, Guarino L, Lusti C, Muir J (2021) Crop diversity, its conservation and use for better food systems. The crop trust perspective. In: Food systems summit brief prepared by research Partners of the Scientific Group for the food systems summit. https://doi.org/10.48565/scfss2021-j983

Serova E, Orlova N, Popov V, Petukhova M, Osmakova A, Kobiakov O, . . ., Tolmachev P (2021) Key areas of the agricultural science development in Russia in the context of global trends and challenges. https://doi.org/10.48565/scfss2021-6265

Shukla et al (2019) Summary for policymakers. In: Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Intergovernmental Panel on Climate Change. https://www.ipcc.ch/site/assets/uploads/sites/4/2020/02/SPM_Updated-Jan20.pdf

Smith P et al (2019) Interlinkages between desertification, land degradation, food security and greenhouse gas fluxes: synergies, trade-offs and integrated response options. In: Shukla PR et al (eds) Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/site/assets/uploads/sites/4/2019/11/09_Chapter-6.pdf

Snapp S, Kebede Y, Wollenberg E, Dittmer KM, Brickman S, Egler C, Shelton S (2021) Delivering climate change outcomes with agroecology in low-and middle-income countries: evidence and actions needed. In: Food systems summit brief prepared by research Partners of the Scientific Group. https://doi.org/10.48565/scfss2021-2420

Sperling F, Havlik P, Denis M, Valin H, Palazzo A, Gaupp F, Visconti P (2020) Transformations within reach: Pathways to a sustainable and resilient world-Resilient Food Systems. http://pure.iiasa.ac.at/16822

Tambo JA, Wünscher T (2017) Farmer-led innovations and rural household welfare: evidence from Ghana. J Rural Stud 55:263

Taylor B, Tonnang HEZ, Beale T, Holland W, Oronje M, Abdel-Rahman EM, Onyango D, Finegold C, Zhu J, Pozzi S, Murphy ST (2021) Leveraging data, models & farming innovation to prevent, prepare for & manage pest incursions: delivering a pest risk service for low-income countries. In: Food systems summit brief prepared by Partners of the Scientific Group. https://doi.org/10.48565/scfss2021-ty56

Thornton PK, Kristjanson P, Förch W, Barahona C, Cramer L, Pradhan S (2019) Is agricultural adaptation to global change in lower-income countries on track to meet the future food production challenge? Glob Environ Chang 52:37–48. https://doi.org/10.1016/j.gloenvcha.2018.06.003

Trigo E, Chavarria H, Pray C, Smyth SJ, Torroba A, Wesseler J, Zilberman D, Martinez JF (2021) The bioeconomy and food systems transformation. In: Food systems summit brief prepared by research Partners of the Scientific Group. https://doi.org/10.48565/scfss2021-w513

Valin H, Hertel T, Bodirsky BL, Hasegawa T, Stehfest E (2021) Achieving zero hunger by 2030 a review of quantitative assessments of synergies and tradeoffs amongst the UN sustainable development goals: a paper from the scientific group of the UN food systems summit. Scientific Group for the UNFSS. https://doi.org/10.48565/scgr2021-2337

Van der Ploeg JD, Barjolle D, Bruil J, Brunori G, Madureira LMC, Dessein J et al (2019) The economic potential of agroecology: empirical evidence from Europe. J Rural Stud 71:46–61. https://doi.org/10.1016/j.jrurstud.2019.09.003

van Vliet S, Kronberg SL, Provenza FD (2020) Plant-based meats, human health, and climate change. Front Sustain Food Syst 4:128. https://doi.org/10.3389/fsufs.2020.00128

Van Zanten HH, Van Ittersum MK, De Boer IJ (2019) The role of farm animals in a circular food system. Glob Food Sec 21:18–22

van Zonneveld M, Volk GM, Dulloo ME, Kindt R, Mayes S, Quintero M et al (2021) Safeguarding and using fruit and vegetable biodiversity. In: Food systems summit brief by Partners of Scientific Group. https://doi.org/10.48565/scfss2021-rz27

van Zutphen KG, Barjolle D, van den Berg S, Gavin-Smith B, Kraemer K, Musard C, Prytherch H, Six J, Winter S, Woltering K (2021) Secondary cities as catalysts for nutritious diets in low- and middle-income countries. In: Food systems summit brief by Partners of Scientific Group. https://sc-fss2021.org/wp-content/uploads/2021/06/FSS_Brief_Secondary_Cities.pdf

von Braun J (2018) Global institutions: governance reform for food, nutrition, and agriculture. Global Food Policy Report, pp 62–71. https://doi.org/10.2499/9780896292970_08

von Braun J (2020) Transforming Food Systems – the challenges of food security, malnutrition, climate change, ecosystems degradation, well-being. In: Presentation at the European Union – FAO Strategic Dialogue (May 06, 2021). https://sc-fss2021.org/wp-content/uploads/2021/05/EU_FAO_JvonBraun_Keynote_6-5-2021.pdf

von Braun J, Kalkuhl M (2015) International Science and policy interaction for improved food and nutrition security: toward an International Panel on Food and Nutrition (IPFN). ZEF Working Paper Series, 142(October)

von Braun J, Zamagni S, Sorondo MS (2020) The moment to see the poor. Science 368(6488):214. https://doi.org/10.1126/science.abc2255

von Braun J, Afsana K, Fresco LO, Hassan M, Torero M (2021a) Food system concepts and definitions for science and political action. Nat Food 2(10):748–750

von Braun J, Bezawit C, Torero MC, Laborde D, Carin S (2021b) Ending hunger by 2030 – policy actions and costs. In: Food systems summit brief prepared by research Partners of the Scientific Group for the food systems summit. https://doi.org/10.48565/scfss2021-kz31

Webb P, Flynn DJ, Kelly NM, Thomas SM, Benton TG (2020a) COVID-19 and food systems: rebuilding for resilience. In: Food systems summit brief by Partners of Scientific Group. https://doi.org/10.48565/scfss2021-g940

Webb P, Benton TG, Beddington J, Flynn D, Kelly NM, Thomas SM (2020b) The urgency of food system transformation is now irrefutable. Nat Food 1(10):584–585. https://doi.org/10.1038/s43016-020-00161-0

Webb P, Flynn DJ, Kelly NM, Thomas SM (2021) The transition steps needed to transform our food systems. In: Food systems summit brief prepared by research Partners of the Scientific Group. https://doi.org/10.48565/scfss2021-hz63

WHO (2020) Dietary recommendations: nutritional requirements; establishing human nutrient requirements for worldwide application. WHO, Geneva. https://www.who.int/news-room/fact-sheets/detail/food-safety

World Economic Forum (2021) The global risks report 2021. http://www3.weforum.org/docs/WEF_The_Global_Risks_Report_2021.pdf

Wouterse F, Badiane O (2019) The role of health and educational attainment in agricultural production: evidence from smallholders in Burkina Faso. Agric Econ 50:4

Zarnowiecki D, Mauch CE, Middleton G, Matwiejczyk L, Watson WL, Dibbs J, Dessaix A, Golley RK (2020) A systematic evaluation of digital nutrition promotion websites and apps for supporting parents to influence children's nutrition. Int J Behav Nutr Phys Act 17(1):17. https://doi.org/10.1186/s12966-020-0915-1

Zilberman D, Lu L, Reardon T (2019) Innovation-induced food supply chain design. Food Policy 83:289–297. https://doi.org/10.1016/j.foodpol.2017.03.010

Zimmermann A, Rapsomanikis G (2021) Trade and sustainable food systems. In: Food systems summit brief by Partners of Scientific Group. https://doi.org/10.48565/scfss2021-zq03