Climate Change and Food Systems

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1 Introduction

Climate change affects the functioning of all of the components of food systems (IPCC 2019) that embrace the entire range of actors and their interlinked value-adding activities involved in the production, aggregation, processing, distribution, consumption, and recycling of food products that originate from agriculture (including livestock), forestry, fisheries, and food industries, and the broader economic, societal, and natural environments in which they are embedded (von Braun et al. 2021). At the same time, food systems are a major cause of climate change, contributing about a third (21–37%) of the total GHG emissions through agriculture

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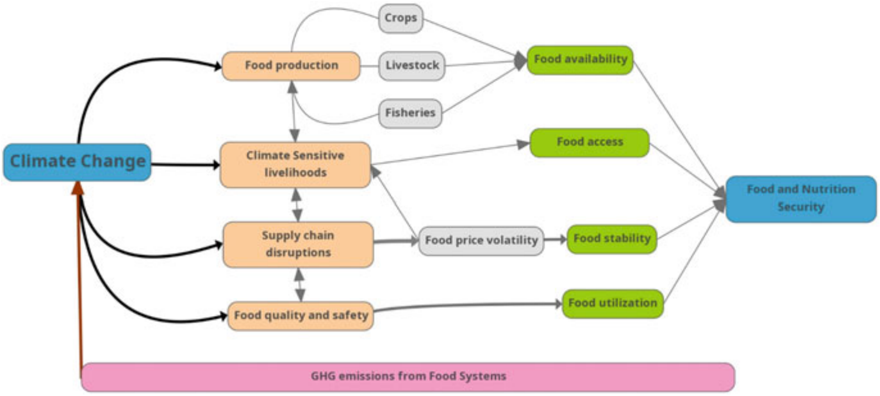

Fig. 1 Linkages between climate change and food systems

and land use, storage, transport, packaging, processing, retail, and consumption (Mbow et al. 2019) (Fig. 1).

Climate change will affect food systems differentially across world regions. While some areas, such as northern temperate regions, may even experience some beneficial changes in the short term, tropical and sub-tropical regions worldwide are expected to face changes that are detrimental to food systems. Such changes will have effects on food and nutrition security through a complex web of mechanisms (Fig. 1). Critical climate variabilities that affect food and nutrition security include increasing temperatures, changing precipitation patterns and greater frequency or intensity of extreme weather events such as heatwaves, droughts and floods (Mbow et al. 2019). They impact the productivity of crops, livestock and fisheries by modulating water availability and quality, causing heat stress, and altering the pests and disease environment, including through the faster spread of mycotoxins and pathogens. Increased frequency and intensity of floods and droughts can lead to considerable disruptions in food supply chains through harvest failures and infrastructure damage. The exposure of people to heatwaves, droughts and floods can harm their health and lower their productivity, affecting their livelihoods and incomes, especially for those engaged in climate-sensitive sectors or working outdoors. This exposure can strongly affect more vulnerable groups in many lower-income countries, e.g., smallholder farmers, low-income households, women and children. Other factors related to climate change that affect food systems are the rise in atmospheric concentrations of CO_2, and, indirectly, land degradation, and a reduction in pollination services. Changes in CO_2 levels in the atmosphere affect both crop yields and their nutrient content. Climate change will exacerbate land degradation through increased soil erosion, especially in sloping and coastal areas, increased soil salinity in irrigated lands, and climates that are more arid and more prone to desertification in some dryland areas (Olsson et al. 2019; Mirzabaev et al. 2019). The potential reduction or loss of pollination services also leads to lower crop yields. Conservative estimates, which consider these climate change impacts only partially, show that the number of people at risk of hunger may increase by 183 million by 2050 under high emission and low adaptation scenario [i.e., under Shared Socioeconomic Pathway (SSP) 3], compared to low emission and high adaptation scenarios (SSP1). An additional 150–600 million people are projected to experience various forms of micronutrient deficiency by 2050 in the higher emission scenario (Myers et al. 2017; Zhu et al. 2018; Medek et al. 2017).

The interactions between climate change and food systems have considerable repercussions across all of the dimensions of sustainable development. In fact, in six of the 17 sustainable development goals (SDGs), climate change-food system interactions increasingly play a major role. These relate to the social goals of zero hunger (SDG 2) and gender equality (SDG5), and the four environmental goals of water resources (SDG 6), climate action (SDG 13), life below water (SDG 14), and life on land (SDG 15). Solutions addressing the challenges posed by climate change-food system interactions can serve as a critical entry point for promoting the 2030 Agenda for sustainable development well beyond the timeline of the current SDGs (Pradhan et al. 2017). Since these interactions vary according to the country's income, region, and population groups (i.e., gender, age, and location of its population), solutions prioritising women, youths, and rural people, i.e., "leaving no one behind," can better leverage the achievements of the SDGs (Warchold et al. 2021).

2 How Climate Change Interacts with Food Systems and Food Security

2.1 Food Availability

Considerable evidence has by now emerged indicating that climate change is already negatively affecting crop production in many areas across the world (Kim et al. 2019; FAO 2018). Reductions of 21% in total factor productivity of global agriculture since 1961 have been estimated (Ortiz-Bobea et al. 2021). It has been found that climate change over the last four-five decades has reduced the yields of cereals by about 2–5% on average globally, compared to the situation if there had been no climate change (Iizumi et al. 2018). This range of about 5% lower cereal yields due to climate change was also found in regional studies, for example, for wheat and barley in Europe (Moore and Lobell 2015), for wheat in India (Gupta et al. 2017), and for maize in Africa, Central and Eastern Asia (Ray et al. 2019), and Central and South America (Verón et al. 2015). Higher losses equalling about 5–20% were found for millet and sorghum yields in West Africa (Sultan et al. 2019), and maize yields in Eastern and Southern Europe were estimated to be lower by about 5–25% (Agnolucci and De Lipsis 2020). There is growing literature documenting the negative impacts of climate change on the yields of legumes, vegetables, and fruits in drylands, tropical and sub-tropical areas (Mbow et al. 2019; Scheelbeek et al.

2018). These losses in yields have occurred after the taking of coping and adaptive actions (Mbow et al. 2019).

In temperate climatic zones, such as northern China, parts of Russia, northern Europe, and parts of Canada, observed climatic changes are increasing the agricultural potentials, leading to higher crop production (Moore and Lobell 2015; Ray et al. 2019; Potopová et al. 2017; Meng et al. 2014; Wang and Hijmans 2019; Bisbis et al. 2018). However, in many areas, this increased production is coming at the expense of lower yield stability due to higher weather variability between seasons. Climate change accounts for about half of food production variability globally. Presently, adaptive strategies for increasing crop yields (crop breeding, improved agronomic management, adaptations based on indigenous and local knowledge, etc.) can withstand, at a global average, any impacts of climate change on said yields. However, the acceleration of climate change can overwhelm this trend in the future; and the impacts are already being experienced in many regions. Climate change increased drought-induced food production losses in southern Africa, leading to 26 million people in the region requiring humanitarian assistance in 2015–2016 (Funk et al. 2018). Climate change is also increasing ocean acidification and temperatures, reducing farmed fish and shellfish production, as well as wild fish catches, with some regions experiencing losses of 15%–35% (Mbow et al. 2019).

The impacts of climate change on food production are projected to worsen after the 2050s, particularly under higher emission scenarios (Mbow et al. 2019). In agriculture, the biggest crop yield declines due to climate change are expected to occur in those areas that are already hot and dry, especially in the tropics and sub-tropics, as well as in the global drylands where water scarcity is projected to become more acute (Mirzabaev et al. 2019). More recent modelling shows that previous projections of climate change impacts on future crop yields underestimated the extent of potential yield declines. For example, many crop modelling studies do not consider the effect of short-term extreme weather events. Although extreme weather events have always posed the threat of disruptions in food systems, climate change is increasing the likelihood of simultaneous crop failures in major crop-producing areas in the world (Anderson et al. 2019; Heino et al. 2020). Disruptions in storage and distribution infrastructures and on food provisioning due to extreme event systems will also impact food availability, as well as bringing about a reduction in food exchanges due to lower productivity (Rivera Ferre 2014).

New twenty-first century projections by the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Rosenzweig et al. 2021a), using ensembles of latest-generation crop and climate models, suggest markedly more pessimistic yield responses for maize, soybean, and rice, compared to the original ensemble. End-of-century maize productivity is shifted from +5 to −5% (SSP126) and from +1 to −23% (SSP585), explained by warmer climate projections and a revised crop model ensemble (Jägermeyr et al. 2021). In contrast, wheat shows stronger high-latitude gains, related to higher CO_2 responses. The 'emergence' of the climate impact signal—when mean changes leave the historical variability—consistently occurs earlier in the new projections, as early as 2030 in several of the main producing regions. While future yield estimates remain uncertain, these results suggest that major breadbasket regions may contend with a changing profile of climatic risks within the next few decades (Jägermeyr et al. 2021). While many fruit, vegetable and perennial crops are understudied, higher temperatures are projected to negatively impact their production, with one study estimating a 4% reduction in fruit and vegetable production as the result of climate change (Springmann et al. 2016).

The impacts of climate change on livestock systems and fisheries have been studied much less than those on the major crops. Nonetheless, considerable evidence indicates that increased frequency of heatwaves and droughts under climate change can lower livestock productivity and reproduction through heat stress, reduced availability of forage, increased water scarcity and the spread of livestock diseases (Mbow et al. 2019; Rojas-Downing et al. 2017). Increased levels of CO_2 can favour the growth of pasture grasses, especially during rainier seasons and in more humid locations (Mirzabaev et al. 2019; Herrero et al. 2016). In contrast, in many arid and semi-arid locations, the projected effects are mostly negative (Rojas-Downing et al. 2017; FAO 2015; Boone et al. 2018). Climate change was found to reduce the maximum sustainable yield of several marine fish populations by about 4% (Free et al. 2019). Every 1 °C increase in global warming was projected to decrease mean global animal biomass in the oceans by 5% (Lotze et al. 2019), as well as redistributing fish populations away from sub-tropical and tropical seas towards poleward areas (Oremus et al. 2020). It is clear that the association between climate change and human nutrition goes beyond issues of caloric availability, and a growing challenge by 2050 will be providing nutritious and affordable diets (Springmann et al. 2016).

2.2 Food Access

The impacts of climate change on agricultural production, supply chains and labour productivity in climate-sensitive sectors will influence both food prices and incomes, strongly affecting people’s ability to purchase food through these price and income changes (Baarsch et al. 2020). Climate change is projected to increase global cereal prices by between 1% to 29%, depending on the Shared Socioeconomic Pathway considered (Mbow et al. 2019). The reductions in the yields of legumes, fruits and vegetables will also lead to higher prices for them. The impacts of these price increases on food access are not straightforward. Net food-selling agricultural producers can benefit from higher food prices (Hertel et al. 2010). Those same higher food prices will primarily hurt the urban poor and net food-buying agricultural producers (Mbow et al. 2019). Increased temperatures and more frequent heatwaves will reduce labour productivity for outdoor work and work in closed areas without air conditioning. Lower labour productivity will result in lower incomes and lower purchasing power.

2.3 Food Stability

Climate change will increase the frequency of extreme water events, such as droughts, floods, hurricanes, and sea storms. Resulting inter-annual variability in food production, the destruction of transportation infrastructures, and greater food price instability can ultimately lead to more volatile global and regional food trade, undermining people's ability to access food in a stable way (Mbow et al. 2019). These disruptions could have a particularly negative impact on land-locked countries with less infrastructural access to the global food trade, as well as vulnerable social groups, especially in those locations without functioning or sufficient social protection schemes (FAO 2018).

2.4 Food Utilisation and Safety

Climate change is projected to adversely impact childhood undernutrition, stunting, and undernutrition-related childhood mortality and increase the number of disability-adjusted life years lost, with the largest risks being in Africa and Asia (Hasegawa et al. 2018a). Moreover, climate-related changes in food availability and diet quality are estimated to result in 529,000 excess climate-related deaths with about 2 °C warming by 2050 (Springmann et al. 2016). Most of these deaths are projected to occur in South and East Asia. Extreme climate events will even increase risks of undernutrition on a regional scale, via spikes in food prices and reduced income. Exposure to one pathway of food insecurity risk (e.g., lower yields) does not exclude exposure to other pathways (e.g., income reduction). Higher concentrations of atmospheric CO_2 reduces the protein and mineral content of cereals, degrading the quality of food and, subsequently, food utilisation (Mbow et al. 2019). Rising temperatures are improving the conditions for the spread of pathogens and mycotoxins, posing risks to human health and increasing food waste and loss (Battilani 2016). Climate change is projected to increase the area of spread of mycotoxins from tropical and sub-tropical areas to temperate zones (Mbow et al. 2019). Reduction in water quality due to climate change will also negatively affect food utilisation.

2.5 Impacts of Food Systems on Climate Systems

GHG emissions from food systems are a major contributor to climate change. Food systems are responsible for about one-quarter of global GHG emissions, or even up to one-third if indirect effects on deforestation are included (21%–37%) (Mbow et al. 2019). Specifically, new estimates by the Food Climate Partnership (Rosenzweig et al. 2021b) show that total GHG emissions from the food system were about 16 CO_2 eq $year^{-1}$ in 2018, or one-third of the total global anthropogenic

GHG emissions. Three-quarters of these emissions, 13 Gt CO_2 eq year^{-1}, were generated either during on-farm production or in pre- and post-production activities, such as manufacturing, transport, processing, and waste disposal. The remainder was generated through land use change of natural ecosystems to agricultural land. Results further indicate that pre- and post-production emissions were proportionally more important in high-income than in low-income countries, and that, during the period 1990–2018, land use change emissions decreased while pre- and post-production emissions increased (Tubiello et al. 2021).

Even if fossil fuel-related emissions were stopped immediately, continuation of the current food system emissions could make the below 2 °C climate target unachievable (Clark et al. 2020). There are significant opportunities for reducing these emissions (Smith et al. 2019),, but at the same time, it is important to bear the food security implications in mind when implementing climate mitigation efforts (Frank et al. 2019; Hasegawa et al. 2018b). Without compensatory policies in place, stringent, abrupt and large-scale application of mitigation options, particularly those that are land-based, can have a negative impact on global hunger and food consumption, with the detrimental impacts being especially acute for vulnerable, low-income regions that already face food security challenges (Hasegawa et al. 2018a). However, many climate solutions can have mitigation and adaptation synergies together with other co-benefits, including for health, livelihood, and biodiversity (Smith et al. 2019; Rosenzweig et al. 2020).

3 Solutions for Climate Change Adaptation and Mitigation in Food Systems

Based on the above assessment, as well as the recent IPCC special report on Climate Change and Land (IPCC 2019), the following actions are proposed for uptake by governments, the private sector and civil society. These actions are of two types. Firstly, there are a wide range of both well-tested, ready-to-go solutions, and potential solutions for climate change adaptation and mitigation within food systems (Herrero et al. 2020) (Actions 1 to 7). Many of these already available solutions are well known and are being applied at local scales around the world, even if not at sufficient levels. Hence, the major effort to unleash their potential would involve overcoming various technical and structural barriers for their much wider application. The second type of action (8 and 9) focuses on key promising solutions that can help us meet the longer-term challenges of climate change within the context of food systems in the second half of this century, when most food production practices will face unprecedented challenges.

1. Amplify efforts for sustainable land management

Sustainable management of land (SLM), which includes water, supports and maintains ecosystem health, increases agricultural productivity, and contributes to climate change adaptation and mitigation (Olsson et al. 2019; Mirzabaev et al. 2019). SLM is defined as the use of land resources, including soils, water, animals and plants, to produce goods that meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions (UN 1992 Rio Earth Summit).

There are many practical examples of SLM. Application of water-efficient irrigation methods such as sprinkler and drip irrigation can help increase resilience to increasing aridity under climate change (Mirzabaev et al. 2019). Adoption of drought-resistant crop cultivars under diversified cropping systems is an essential adaptive strategy in many dryland areas (Mirzabaev et al. 2019). Where suitable, agroforestry is a powerful practice for reducing soil erosion and increasing carbon sequestration, while diversifying livelihoods (Smith et al. 2019). Rangeland management systems based on sustainable grazing and re-vegetation can increase rangeland resilience and long-term productivity while supporting a wide range of ecosystem services. Agroforestry practices, shelterbelts and silvio-pasture systems help reduce soil erosion and sequester carbon, while increasing biodiversity that supports pollination and other ecosystem services (Kuyah et al. 2019). SLM also includes agroecological practices, such as use of organic soil amendments, crop diversification, cover crops, intercropping, conservation agriculture practices, etc., that can have positive impacts on ecosystem services, food security and nutrition (Bezner Kerr et al. 2021; Beillouin et al. 2019; Muller et al. 2017; Tamburini et al. 2020; Kremen and Merenlender 2018). Indigenous knowledge and local knowledge hold a great array of practices for SLM (Rivera Ferre et al. 2021). Protection, restoration and climate-friendly management of peatlands are key elements for ambitious emission reduction strategies (Humpenöder et al. 2020).

Although SLM has been proven to provide positive social and economic returns, the adoption is currently insufficient. Important barriers for adoption are access to the resources for changing practices and the time required for the new practices to become productive. Introduction of payments for ecosystem services and subsidies for SLM can help. Enabling policy frameworks that include both incentives and disincentives are needed for promoting the adoption of SLM. Land tenure considerations are a major factor contributing to the adoption of SLM (Olsson et al. 2019), particularly for women. Various forms of collective action are crucial for implementing SLM in both privately and communally managed lands (Pretty 2003), although such efforts need to be strengthened and supported by policy (Isgren 2018). A greater emphasis on understanding gender-specific differences over land use and land management practices can promote SLM practices more effectively. Improved access to markets, including physical (e.g., transportation), economic (e.g., fair prices), and political (e.g., fair competition) support, raises agricultural profitability and motivates investment into climate change adaptation and SLM. Developing, enabling and promoting access to clean energy sources and technologies can contribute to reducing land degradation and mitigating climate change through decreasing the use of fuelwood and crop residues for energy, while significantly improving health for women and children (Sana et al. 2019). Finally, looking at co-benefits between addressing climate change (adaptation and mitigation) and other urgent problems, like land degradation and biodiversity conservation, much can be gained by promoting SLM in agriculture.

2. Promote open and equitable food trade

The very heterogeneous effects of climate change on food production worldwide and the increase in extreme weather events that disrupt local food production activities highlight the importance of international food trade as a key adaptation option to this volatile environment (Van Meijl et al. 2018; Stevanović et al. 2016). At the same time, strengthening regional and local food systems, through policies and programmes that support sustainable local production, can help build a resilient food system. Such policies can include support for urban and peri-urban production, public procurement, and subsidies that encourage the application of sustainable production approaches.

Adapting to changing climate will require a combination of enhanced regional and local food trade, as well as international food trade, that can act as safety nets in the context of climate crises. To this aim, reducing transaction costs of food trade and maintaining transparent and well-enforced international food trade governance can strengthen food systems' resilience. This will particularly include avoiding imposing export bans. Food trade and food sovereignty are complementary elements of food security, and should not be regarded as mutually exclusive; rather, transparent and fair norms need to be agreed upon.

Fiscal instruments (e.g., carbon taxes) need to be given high priority in order to reduce fossil fuel use in agriculture. Agricultural subsidies need to be adjusted to encourage the application of sustainable production approaches and make sure that any negative effects that arise from them will be reduced through trade, and they need to take power differences into account, e.g., the impacts of subsidised food exports by high-income countries that make it harder for farmers in low-income countries to use sustainable methods or sell their products. Trade agreement mechanisms that allow low-income countries to have an equal say in trade governance are needed.

3. Include food systems in climate financing at scale

Food systems represent a range of actors and their interlinked value-adding activities that are most impacted by climate change. Food systems are also a major source of GHG emissions. This makes food systems a high priority target for adaptation and mitigation investments. However, investments into climate change adaptation and mitigation in food systems to date have only accounted for a tiny fraction of the total amounts of climate finance. Investments into climate change mitigation in food systems need to be commensurate with the share of GHG emissions coming from those systems, i.e., about a third of all mitigation funding, which is presently dominated by the energy sector and infrastructure. To illustrate, there are considerable opportunities for climate change adaptation and mitigation through investments into land restoration (e.g., reforestation, sustainable land management, re-seeding degraded rangelands) that allow for sequestering carbon in soils, increasing crop and livestock productivity and providing a wide range of other ecosystem services.

Estimates show that every dollar invested in land restoration yields anywhere from 3 to 6 dollars of return, depending on the location across the world (Nkonya et al. 2015). Investments in food value chains for reducing food waste and loss is another area with substantial mitigation and adaptation benefits. A wide range of public and private sources could be harnessed for these investments, such as increasing substantially the annual development aid dedicated to agricultural and rural development, food and nutrition security, increased investments by international and regional development banks in food systems, and more active involvement of the private sector (e.g., green bonds) and philanthropies.

4. Strengthen social protection and empowerment of the vulnerable

It is now practically impossible to fully adapt to climate change impacts. Even without climate change, extreme weather events periodically inflict significant disruptions on food systems at the local, regional and even global levels. Climate change will make these disruptions more frequent and more extensive. Therefore, it is essential to strengthen the social protection for vulnerable populations in terms of accessing food during the times of such disruptions. Social protection can involve many forms, such as access to subsidised food banks, cash transfers, insurance products, pension and employment guarantee schemes, weather index insurance, and universal income.

The impacts of climate change on food systems are not suffered equally by all social groups. Age, class, gender, race, ethnicity, and disability, among others, are social factors that make some people more vulnerable than others. Actions to address such inequality and differential impacts imply, on the one hand, strengthening social protection and, on the other hand, empowering marginalised social groups through collective action. Empowering women in societies increases their capacity to improve food security under climate change, making substantial contributions to their own well-being, that of their families and that of their communities. Women's empowerment is crucial to creating effective synergies among adaptation, mitigation, and food security, including targeted agriculture programmes to change socially-constructed gender biases (Kerr et al. 2016). Empowerment through collective action and groups-based approaches in the near-term has the potential to equalise relationships on the local, national and global scales (Ringler et al. 2014).

5. Encourage healthy and sustainable diets

Transitioning to more healthy and sustainable diets and minimising food waste could reduce global mortality from 6% to 19% and food-related GHG emissions by 29%–70% by 2050 (Springmann et al. 2016; Willett et al. 2019). According to the WHO, healthy diets are essential to end all forms of malnutrition and protect people from non-communicable diseases, including diabetes, heart disease, stroke and cancer. Currently, food consumption deviates from healthy diets with either too much (e.g., red meat and calories) or too little (e.g., fruits and vegetables) food and nutrition supply (Pradhan and Kropp 2020). Healthy diets have an appropriate calorie intake, according to gender, age and physical activity level. They are mainly composed of a diversity of plant-based foods, including coarse grains, pulses, fruits and vegetables, nuts, and seeds, with low amounts of animal source foods (Willett et al. 2019). The current diets of many high-income countries comprise a large share of animal source foods that are emission-intensive, with red meat consumption higher than the recommended value. Simultaneously, consumption of fresh fruits and vegetables is below the recommended value in most countries (Bodirsky et al. 2020).. Changes towards healthier diets have a mitigation potential of 0.7–8.0 $GtCO_2$-eq $year^{-1}$ by 2050, but social, cultural, environmental, and traditional factors need to be considered to achieve this potential at broad scales (Mbow et al. 2019; Rosenzweig et al. 2020). One critical problem is that, currently, healthy diets are unaffordable to broad sections of societies, even in high-income countries. Sustainable and healthy diets based on diversified intake are often linked to diversified production systems, highlighting the linkages between production and consumption (Chepkoech et al. 2020).

To encourage dietary transitions towards healthy and sustainable diets, a full range of policy instruments, from hard to soft measures, is needed (Willett et al. 2019). For example, unhealthy consumption of emission-intensive animal source foods can be disincentivised by applying taxes and charges, whereas adequate consumption of healthy foods such as fruits and vegetables can be incentivised by providing subsidies and raising consumer awareness. Importantly, policies promoting healthy diets need to pay due consideration to the differential roles of animal source foods in different parts of the world and the important role livestock can play in sustainable agriculture. For example, a recent study from Nepal, Bangladesh and Uganda showed a reduction in stunting in young children due to adequate intake of animal source foods (Zaharia et al. 2021).

6. Reduce GHG emissions from the food systems

Before promoting particular changes to the food systems, it is important to have an overview of where the most important potentials for reducing GHG emissions are. Agriculture is responsible for about 60% (or even 80%, if the indirect land use change is included) of total GHG emissions from the global food system (Mbow et al. 2019). One important message from a systematic meta-analysis of 38,700 farms and 1,600 food processors is the wide range of emissions – about a 50-fold difference between the best and worst practices (Poore and Nemecek 2018). This means that political and economic measures can achieve major reductions in GHG emissions from existing food systems by more broadly applying current best practices and without waiting for new technologies or behaviour changes.

Reducing GHG emissions requires integrated interventions both at the production and consumption sides. On the production side, all of those practices that increase soil organic matter contribute to both adaptation and mitigation, while also decreasing soil degradation and erosion. Globally, cropland soils have lost an estimated 37 GtC (136 Gt CO_2) since the Neolithic revolution (Sanderman et al. 2017); recapturing that lost carbon through SLM would not only contribute to climate change mitigation, it would also increase the ecological resilience of agro-ecosystems and provide opportunities for income and employment in rural societies. A wide range of practices exist, e.g., conservation agriculture practices, lower GHG emissions from fertilisers, agroecology-based approaches, agroforestry or the integration of agriculture and livestock systems that have an estimated potential to sequester 3–6.5 $GtCO_2$-eq/year (Arneth et al. 2021). In rangelands as well, extensive and mixed farming systems, through improved management practices, have the capacity to reduce emissions. Presently, there are between 200 and 500 million pastoralists in the world who act as stewards for 25% of the world's land (Niamir-Fuller 2016).

Meat and dairy consumption is often considered a major culprit of high GHG emissions from food systems, but the discussion often lacks nuance. It is clear that the overall emissions from consumption of animal protein (mainly meat and dairy products) must be reduced to achieve mitigation targets compatible with the Paris Agreement. However, in some regions of the world, an increased consumption of animal protein would be desirable from a health perspective. It is also clear that livestock plays an important role in sustainable food systems – in particular, extensive livestock can help to reduce the need for mineral fertilisers, and they can produce food from areas unsuitable for growing crops (notably, drylands, cold regions and mountainous regions). Finally, expansion of post-harvest processing, refrigeration, subsidy shifts and behavioural changes are needed to reduce food loss and waste and lower the consumption of animal products in those places where intake is too high. Incentives for emission reductions should also be given to agricultural producers by applying GHG emission taxes in agriculture, or including agriculture in existing emission trading schemes.

7. Support urban and peri-urban agriculture

Promoting urban and peri-urban agriculture (PUA) can help increase the resilience of local and regional food systems, create jobs, and, under certain conditions, help reduce GHG emissions from food transportation (Pradhan et al. 2020) and decrease uncertainties that may be associated with disruptions in food systems. PUA includes crop production, livestock rearing, aquaculture, agroforestry, beekeeping, and horticulture within and around urban areas (Clinton et al. 2018). Around 1 billion urban inhabitants (i.e., 30% of the global urban population) can be nourished by producing food through PUA (Kriewald et al. 2019). Simultaneously, PUA can support the regionalisation of food systems, reducing emissions from food transportation (Pradhan et al. 2020). Moreover, PUA is multi-functional and is practised to follow various purposes: it helps to improve food security, generate income, provide employment (Poulsen et al. 2015; Warren et al. 2015), especially for women and youths, and reconnect urban habitants with nature cycles. Subsequently, PUA not only has great potential to reduce poverty and improve nutrition, but also provides a series of ecosystem services such as reduced urban heat island effects (Li et al. 2014) or the fixation of atmospheric nitrogen and carbon when using the appropriate vegetation (Beniston and Lal 2012), thus contributing to climate change mitigation and adaptation. PUA also comprises elements of a circular economy, in which household organic waste can be used as livestock and poultry feed, rather than treated as waste (Ibrahim and Elariane 2018), subsequently reducing environmental pollution and GHG emissions. PUA contributes to increasing the resilience of urban poor households to food price shocks. Previous research on PUA showed that it was the main and only economic activity of poor urban households in many low-income countries. And even when PUA is not the main economic activity of poor urban households, it made a significant contribution to smoothening seasonal food consumption shocks among the urban poor (Poulsen et al. 2015).

8. Invest in research

There have been tremendous advances in better understanding of the interactions between climate change and food systems in recent decades (IPCC 2019; Wheeler and Von Braun 2013). These investments in research and science need to be expanded into the future, not least to ensure viable agricultural systems in the long term when climate change will expose current staple food crops to unprecedented stress. Areas for investment include agroecological approaches to food production, which have so far received far lower investment (HLPE 2019), the breeding of drought-resistant crop cultivars and cultivars with improved nitrogen use to avoid emission of N_2O (Coskun et al. 2017), improved understanding of climate change impacts on both staple and non-staple foods, including impacts on the nutrition values of crops (Soares et al. 2019), particularly vegetables and fruits, and the subsequent implications for healthy diets and the full costs of said diets. Along with these environmental dimensions, increased investment in research on the social and economic impacts of climate change are needed, for example, in such areas as understanding the impacts of climate change and mitigation and adaptation options on vulnerable groups, research on participatory and transdisciplinary approaches to facilitating dialogue between indigenous and scientific knowledge, research on collective action, social innovation and mechanisms to increase food security.

9. Support perennial crop development and cultivation

About 87% of the world's harvested area is cultivated with annual crops, mainly grains (cereals, oilseeds, and pulses) that are germinated [?] and re-sown every year/season (Monfreda et al. 2008). A shift to perennial grain crops would drastically cut GHG emissions from agriculture, and even turn cropping into a carbon sink, while significantly reducing erosion and nutrient leakage. Continued climate change is rendering our existing cultivars increasingly vulnerable to stress, and will ultimately make them unfit for many regions of the world (Altieri et al. 2015). New perennial cultivars have the potential to create cropping systems that are genuinely adapted for the climatic conditions towards the second half of this century. Perennial crops have the potential to drastically reduce the costs of farming by cutting the need for external inputs (seeds, fertilisers, pesticides, machinery, energy, and labour), and hence generate social and economic advantages, particularly or farmers and rural societies (Crews et al. 2018).

Development of new perennial grain crops through *de novo* domestication and wide hybridisation have advanced tremendously in the last decade, thanks to scientific and technological advancements such as genomic selection technology (Crain et al. 2021). The key benefits of perennial crops are that their widespread root systems can help sequester carbon in the soils for extended periods of time, water and minerals are used more efficiently by perennial plants, and weeds are more effectively managed (Crews et al. 2018; DeHaan et al. 2020). They are also exceptionally drought-resistant and can bring soil erosion and nutrient-leaching to a practical minimum (Crews et al. 2016). There are already commercial cultivars of perennial rice (Zhang et al. 2021) and successful semi-commercial experiments with perennial Kernza, a wheat relative (Lanker et al. 2020). The yields of Kernza are still low compared to conventional wheat, but continued breeding can result in a competitive perennial alternative to wheat in 20–25 years (Bajgain et al. 2020). A range of other crops is in the pipeline for domestication and breeding as perennial crops, such as barley, oilseeds and pulses. Equally important is the development of perennial polycultures, such as the intercropping of perennial grains and legumes, making the system more or less self-sufficient in nitrogen. These results are proof of concept that high yielding perennial cultivars can be developed within the timeframe of a few decades, but research on all aspects of such a "perennial revolution" is urgently needed.

4 Conclusion

This chapter has two central messages. The bad news is that climate change is projected to affect food systems around the world significantly, often in ways that exacerbate existing frailties/weaknesses and inequalities among regions of the world and groups in society. The good news is that many practices, technologies, and wells of knowledge and social capital already exist to address climate change constructively, in terms of both mitigation and adaptation, as well as synergies between them and co-benefits with other important goals such as the conservation of biodiversity and other ecosystem services. Therefore, food systems can and should play a much bigger role in climate policies. In the short term, pro-poor policy changes and support systems can unleash a range of positive changes well beyond food systems without delay. In the long term, there is an urgent need to invest in research to ensure food security and ecosystem integrity for coming generations.

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