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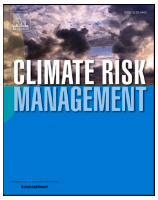

Severe climate change risks to food security and nutrition

Alisher Mirzabaev [a], Rachel Bezner Kerr [b], Toshihiro Hasegawa [c], Prajal Pradhan [d,h], Anita Wreford [e], Maria Cristina Tirado von der Pahlen [f], Helen Gurney-Smith [g]

[a] *Institute for Food and Resource Economics, Bonn University, Germany*
[b] *Department of Global Development, Cornell University, USA*
[c] *Institute for Agro-Environmental Sciences, National Agriculture and Food Research Organization, Japan*
[d] *Potsdam Institute for Climate Impact Research, Member of the Leibniz Association, Potsdam, Germany*
[e] *Agribusiness & Economics Research Unit, Lincoln University, New Zealand*
[f] *School of Public Health, University of California Los Angeles, USA*
[g] *St. Andrews Biological Station, Fisheries and Oceans Canada, Canada*
[h] *Bauhaus Earth, Berlin, Germany*

ABSTRACT

This paper discusses severe risks to food security and nutrition that are linked to ongoing and projected climate change, particularly climate and weather extremes in global warming, drought, flooding, and precipitation. We specifically consider the impacts on populations vulnerable to food insecurity and malnutrition due to lower income, lower access to nutritious food, or social discrimination. The paper defines climate-related “severe risk” in the context of food security and nutrition, using a combination of criteria, including the magnitude and likelihood of adverse consequences, the timing of the risk and the ability to reduce the risk. Severe climate change risks to food security and nutrition are those which result, with high likelihood, in pervasive and persistent food insecurity and malnutrition for millions of people, have the potential for cascading effects beyond the food systems, and against which we have limited ability to prevent or fully respond. The paper uses internationally agreed definitions of risks to food security and nutrition to describe the magnitude of adverse consequences. Moreover, the paper assesses the conditions under which climate change-induced risks to food security and nutrition could become severe based on findings in the literature using different climate change scenarios and shared socioeconomic pathways. Finally, the paper proposes adaptation options, including institutional management and governance actions, that could be taken now to prevent or reduce the severe climate risks to future human food security and nutrition.

1. Introduction

Food security is defined as “a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life” (FAO et al., 2018). Food security includes such dimensions as food availability, access, utilization, stability over time, as well as agency, and sustainability (HLPE 2020). The climate change risk to food security refers to the breakdown of food systems, including crops, livestock, and fisheries, as well as disruptions in food distribution, linked to global warming, drought, flooding, and precipitation variability and extremes, particularly for populations already vulnerable to food insecurity due to lower income, lower physical access to nutritious food, social discrimination or other factors (O’Neill et al., 2022).

This paper builds on the assessment of key risks, i.e. potentially severe risks, to food security and nutrition by the authors reported in O’Neill et al. (2022). Firstly, it provides a more detailed discussion of the findings from the underlying literature, including more recent publications. Secondly, here we additionally also explore in more detail opportunities and limits for adaptive actions to reduce severe climate change risks to future human food security and nutrition (FSN).

The methodology used in the paper is consistent with the approach applied for assessing key risks in the IPCC Working Group 2 report (IPCC AR6 WG2) by O’Neill et al. (2022). This identification of key risks also relies on the assessment of the relevant literature

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conducted in Bezner Kerr et al. (2022), Chapter 5 of IPCC AR6 WG2. Firstly, 13 key risks to FSN were identified across such categories as risks related to food security and malnutrition, risks related to food safety and dietary health, risks related to livelihood of people in the food and ecosystem service sector, risks to ecosystem services, and climate policy related risks (O'Neill et al., 2022). Then, these 13 key risks were aggregated into a representative key risk (RKR) of climate change to FSN.[1] Based on this, a detailed assessment was done on the impact of climate change on: 1) number of people at risk of hunger, and 2) number of people at risk of malnutrition, using the methodology for evaluating severe climate change risks developed under the IPCC AR6 WG2 (O'Neill et al., 2022). The key feature of this methodology is the recognition that the understanding of what constitutes severe risks is highly influenced by values which vary substantially from context to context. Therefore, the methodology uses a set of four criteria to analytically frame potentially severe risks, namely: magnitude of adverse consequences, likelihood of adverse consequences, timing of the risk, and the ability to respond to the risk (Section 2, Table 1). Severe risks should, however, not be considered as only global-scale specific, as they can also realize at local levels. Section 2 describes in more detail the application of this methodology to FSN. The assessment of climate change risks to FSN primarily relies on modeling studies. Caveats to these modelling studies are that most models (crop models in particular) are designed for long-term change in climate but are not suited to project the impacts of short-term extreme events. Finally, the inclusion of adaptation measures into modeling estimates remains selective and partial.

2. Defining severe climate change risks to food security and nutrition (FSN)

In this paper, severe climate change risk to food security is defined using a combination of four criteria, including the magnitude of adverse consequences, the likelihood of adverse consequences, the timing of the risk, and the ability to respond to the risk (Table 1). Severe climate change risks to FSN are those which result, with high likelihood, in pervasive and persistent food insecurity and malnutrition for millions of people, have the potential for cascading effects beyond the food systems, and for which we have limited ability to prevent or fully respond.

In terms of the magnitude of adverse consequences, considering the Sustainable Development Goal 2 on achieving Zero Hunger by 2030, the level of food insecurity in the world is already high, with 720 million to 811 million people being currently undernourished, while about 2.3 billion people being affected by malnutrition (FAO et al., 2021). Differentiating chronic food insecurity from acute food insecurity, the Integrated Food Security Phase Classification indicates that currently, 200,000 people are at a catastrophic food insecurity level, while 32.3 million people are at an emergency level of food insecurity, 112.3 million people are at a crisis level of food insecurity, and 210 million people at the stressed stage of food insecurity (The Integrated Food Security Phase Classification (IPC), 2022). These classification criteria by IPC are based on both first-level outcomes (changes in food consumption and livelihoods), second-level outcomes (nutritional status and mortality), as well as contributing factors (food availability, access, utilization, and stability, hazards and vulnerability) (IPC Global Partners 2021). For example, catastrophic food security implies that "households have an extreme lack of food and/or other basic needs even after full employment of coping strategies. Starvation, death, destitution, and extremely critical acute malnutrition levels are evident" (IPC 2022). The present paper discusses severe climate change risks to food security and nutrition, thus, does not contradict IPC classifications of food insecurity and malnutrition *per se*, but rather complements them.

The two key risks posed by climate change highlighted in this paper are the number of people at risk of hunger and the number of people at risk of malnutrition. Climate change is projected to affect these risks to FSN through such driving mechanisms as agricultural productivity declines, reduced incomes, emerging food safety issues and disruptions in food distributions, as well as by lower nutrient content of some crops and changes in diet quality (Bezner Kerr et al., 2022).

Moreover, climate change is projected to exacerbate the magnitude and likelihood of adverse consequences to food security and nutrition. The timing of these impacts and our ability to respond to them varies based on the level of greenhouse gas (GHG) emissions and shared socioeconomic pathways (SSPs). A further small increase in the severity of the climate change-induced risks to FSN could be expected until 2050. However, there is some evidence that severity of risks to FSN from climate change is projected to increase more strongly after 2050 towards 2080 (Bezner Kerr et al., 2022).

The impacts of climate change on the number of people at risk of hunger and malnutrition are mediated through such drivers as a decline in agricultural productivity, lower incomes from climate-sensitive livelihoods, emerging food safety issues, and disruptions in food distributions (Bezner Kerr et al., 2022). The severity of climate change risk to nutrition is directly related to CO_2 levels in the atmosphere. The rise in atmospheric concentrations of CO_2 is projected to increase crop yields (although moderated by other climate risk factors) (Myers et al., 2017; Zhu et al., 2018) (Fig. 1).

3. Severe climate change risks to FSN

In terms of observed impacts of climate change to FSN, although specific attributional studies are limited by the complex, multi-causal nature of food insecurity and lack of long-term data (Phalkey et al., 2015; Cooper et al., 2019), available indirect evidence suggests that at least some of these currently observed numbers of food insecure people could be due to extreme weather events (FAO et al., 2021). There are some attributional studies of previous events, such as Verschuur et al. (2021) who studied the 2007 drought in

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[1] Key risks have potentially severe adverse consequences for humans and social-ecological systems resulting from the interaction of climate related hazards with vulnerabilities of societies and systems exposed. Representative Key Risks (RKRs) are representative, thematic clusters of key risks (O'Neill et al., 2022).

Table 1
Defining the severity of climate change risks to food security and nutrition (FSN).

Key risk criteria	Number of people at risk of hunger	Number of people at risk of malnutrition
Set of climate drivers	Agricultural productivity declines, reduced incomes, emerging food safety issues and disruptions in food distributions	Lower nutrient content of some crops and changes in diet quality, emerging food safety issues and disruptions in food distributions
(1) Magnitude of adverse consequences	Millions of people in acute food insecurity threatening their lives, livelihoods or both	Millions of people in acute malnutrition threatening their lives, livelihoods or both
(2) Likelihood of adverse consequences	Adverse consequences are already occurring, and the chances of their exacerbation under climate change are high.	
(3) Timing of the risk	A further small increase in severity until 2050, with severity increasing more strongly after 2050 towards 2080	
(4) Ability to respond to the risk	Currently, theoretically, we can respond to risk, but not always successfully. Increased adaptation can limit the exacerbation of food insecurity in future.	

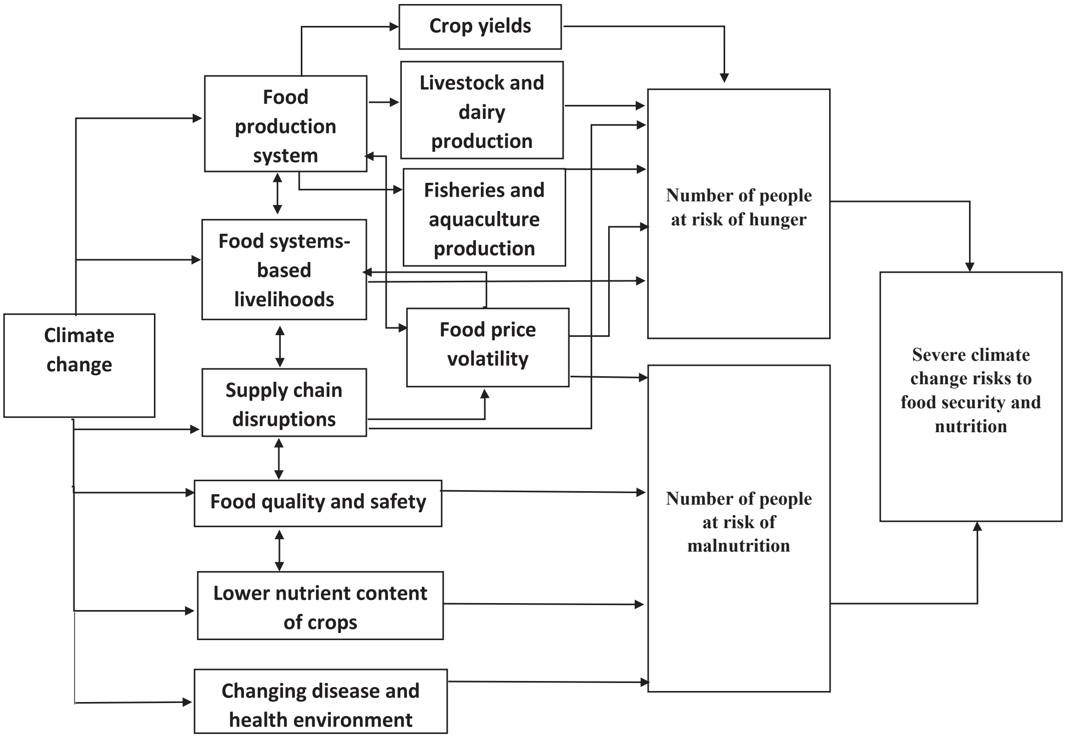

Fig. 1. Impact pathways from climate change to hunger and malnutrition.

Lesotho, and found robust evidence that human-induced climate change exacerbated the drought, with increased food shortages, price increases and acute food insecurity. Similarly, there is an attributional study of the 2015/16 El Niño event that shows how anthropogenic climate change increased crop production losses from drought (Funk, 2018).

For projected impacts if climate change on FSN, we find that climate change will pose severe risks in terms of increasing the number of undernourished people, affecting tens to hundreds of millions of people under high vulnerability (Shared Socioeconomic Pathways (SSPs) 3 and 4) and high emission scenarios (Representative Concentration Pathway RCP8.5), particularly among vulnerable populations in low-income countries. Extreme weather events will increase the risks of undernutrition even on a regional scale via spikes in food prices and reduced income (Mbow et al., 2019; FAO, 2018; Hickey and Unwin, 2020; Hasegawa et al., 2021; Zhang et al., 2022). Moreover, climate change risks of micronutrient deficiency will become severe in high vulnerability development pathways (SSPs 3 and 4) in the absence of societal adaptation, leading to hundreds of millions of additional people lacking key nutrients at atmospheric CO_2 levels above 500 ppm (Myers et al., 2017; Mbow et al., 2019; Maire et al., 2021; Semba et al., 2022). The scale of risks, from local to global, will depend on the level of warming, with lower levels of warming posing locally severe risks to FSN, while higher levels of warming engendering globally severe risks to FSN (O'Neill et al., 2022).

3.1. Risk to hunger

Climate change reduces the productivity of crops, livestock, fisheries and aquaculture by modulating water availability and quality, causing heat stress, shifting phenology, and altering the pests and disease environment, including the faster spread of mycotoxins and pathogens. Increased frequency and intensity of floods, droughts, storm surges and extreme events can lead to considerable disruptions in food supply chains through harvest failures and infrastructure damage, and create competition across food production systems (Cottrell et al., 2019). For example, climate extremes are becoming more frequent, co-occurring, and persistent in Europe, which is a net food exporter (Pradhan et al., 2022).

The exposure of people to heatwaves, droughts, and floods can harm their food security, health and nutrition and lower their productivity affecting their livelihoods and incomes, especially for those engaged in climate-sensitive sectors or working outdoors (de Lima et al., 2021; Kuhla et al., 2021). This exposure can strongly affect more vulnerable low- and middle-income countries, those that rely on rainfed agriculture~~,~~ and particular social and economic groups, e.g., smallholder farmers and farmworkers, low-income households, elderly, women, and children (de Lima et al., 2021; Kuhla et al., 2021).

The updated projections by the Agricultural Model Inter-comparison and Improvement Project (AgMIP) (Rosenzweig et al., 2021) using ensembles of latest-generation global gridded crop models and climate scenarios (Coupled Model Inter-comparison Project, Phase 6) show that the maize productivity declines by −5% under the combination of SSP1 and RCP2.6, and by –23 % under the combination of SSP5 and RCP8.5 scenarios (Jägermeyr et al., 2021). Higher temperatures are projected to negatively impact the production of fruits and vegetables, leading to their lower consumption (Springmann et al., 2016). About one-third of the currently suitable area for major crops and livestock production may become unsuitable by the end of the century under SSP5-8.5 (Kummu et al., 2021). Simultaneous maize yield losses in major-producing regions are projected to surge as the warming level rises from 1.5 °C to 2 °C (Gaupp et al., 2019) and 4 °C (Tigchelaar et al., 2018). Disruptions in storage and distribution infrastructures and food provisioning due to extreme events systems will also impact food availability and diversity (Bezner Kerr et al., 2022), as well as reductions in food exchanges due to lower productivity (Rivera Ferre, 2014).

The impacts of climate change on livestock systems and fisheries are studied much less than for major crops (Rivera-Ferre et al., 2016; Godde et al., 2021). Still, considerable evidence indicates that the 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). In many arid and semi-arid locations, the projected effects of climate change on the productivity of pastures are mostly negative (Boone et al., 2018; FAO, 2015; Rojas-Downing et al., 2017). Under high emission scenarios, exposure to extreme heat stress to livestock is projected to increase for all major species in many parts of the tropics and some temperate zones, risking the viability of outdoor livestock keeping (Thornton et al., 2021).

Global warming has led to an average 4 % decline in marine fisheries productivity and up to 35 % for some regions (Free et al., 2019), where each 1 °C increase is projected to decrease average global animal ocean biomass by 5 % (Lotze et al., 2019) and reduce fisheries catch potential between 5.3 and 7 % by 2050 (Cheung et al., 2019). Warming is also inducing poleward shifts in marine and freshwater aquatic species, leading to changes in fisheries species and abundances in exclusive economic zones (Pinsky et al., 2020; Oremus et al., 2020), and increasing risk for tropical low-income countries (Bindoff et al., 2019). Poleward shifts in suitable habitat, culture species, and productivity are also being observed for mariculture (Weatherdon et al., 2016) and are projected to continue, leading to species and habitat reductions for tropical and sub-tropical regions (Oyinlola et al., 2020; Stewart-Sinclair et al., 2020; Froehlich et al., 2018). The increased occurrence and severity of marine heat waves is projected to increase, leading to reproductive failures, increased mortalities and reductions in maximum catch potentials for fisheries and aquaculture, with associated negative impacts for reliant coastal communities (Cheung et al., 2021; Green et al., 2019; Smale et al., 2019). Ocean acidification is negatively affecting shellfish aquaculture and shellfisheries productivity (Doney et al., 2020; Ekstrom et al., 2015), and is projected to continue to negatively affect major production areas (Chapman et al., 2020; Des et al., 2020; Rheuban et al., 2018). Inland fisheries and aquaculture productivity is projected to continue being negatively affected by climate-induced coastal inundation, drought, flooding and freshwater availability (Lebel et al., 2020; Mehvar et al., 2019; Oppenheimer et al., 2019; Beveridge et al., 2018; Dabbadie et al., 2018).

The severity of climate change risk affecting the number of hungry people worldwide depends on the timing of these impacts. The ability to respond to these impacts varies based on the level of GHG emissions and the characteristics of the corresponding SSPs.

Under a low vulnerability development pathway (SSP 1), climate change starts posing a moderate risk to food security above 1 °C of global warming (i.e., impacts become detectable and attributable to climate-related factors), while beyond 2.5 °C the risk becomes high (widespread impacts on larger numbers or proportion of population or area, but with the potential to adapt or recover) (Hurlbert et al., 2019).

In a medium vulnerability-high warming scenario (SSP2, RCP6.0), accounting for the CO_2-fertilization effect, Hasegawa et al. (2018) projects that the number of undernourished people increases by 24 million in 2050, compared to outcomes without climate change. This number increases by around 78 million in a low warming scenario (RCP2.6) with less CO_2-fertilization effect, while accounting for the impacts of both climate change and mitigation policies.

Under a high vulnerability-high warming scenario (i.e., SSP 3-RCP 6.0), up to 183 million additional people are projected to become undernourished in low-income countries due to climate change by 2050 (Mbow et al., 2019). Climate-related changes in food availability and diet quality are estimated to result in a crude mortality rate of about 54 deaths per million people with about 2 °C warming by 2050 (SSP2, RCP8.5), most of them projected to occur in South and East Asia (67–231 deaths per million depending on the country) (Springmann, 2016).

3.2. Risk to nutrition

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. The increase and severity of extreme events increases the risk of acute food insecurity and malnutrition (Bezner Kerr et al., 2022).

Climate change will affect many determinants of micronutrient deficiency, particularly availability and access to fruits and vegetables (Springmann et al. 2016; Fanzo et al., 2018). Climate change is projected to adversely impact child undernutrition and stunting, undernutrition-related childhood mortality, diet-related morbidity and mortality and increase disability-adjusted life years lost, with the largest risks in Africa and Asia (Springmann et al. 2016; Sulser et al., 2021). Early childhood stunting will have life-long health implications, with intergenerational transmission of malnutrition effects, e.g., childhood stunting of mothers is associated with low birth weights of their children (Fanzo et al., 2018).

Higher concentrations of atmospheric CO_2 reduce the protein and mineral content of cereals, reducing food quality and, subsequently, leading to a higher number of people affected by micronutrient deficiency (Mbow et al., 2019). The concentration of many micronutrients in crops (e.g., phosphorus, potassium, calcium, sulphur, magnesium, iron, zinc, copper, and manganese) can decrease by 5–10 % under atmospheric CO_2 concentrations of 690 ppm (3.5 °C warming). The decline in zinc content is projected to lead to additional 150–220 million people being affected by zinc deficiency, with increasing existing deficiencies in more than 1 billion people (Myers et al., 2017). Similarly, a decrease in protein and micronutrient content in rice due to a higher CO_2 concentration (568 to 590 ppm) can lead to 600 million people with rice as a staple at risk of micronutrient deficiency by 2050 (Zhu et al., 2018). Additionally, the impact on the protein content of increased CO_2 concentration (greater than500 ppm) can lead to an additional 150 million people with protein deficiency by 2050 (within the total of 1.4 bln people with protein deficiency) in comparison to the scenario without increased CO_2 concentration (Medek, 2017).

3.3. *Interaction with other risks*

Climate change risks to FSN strongly interact with other social and economic risks to FSN, often amplifying each other's impacts (Challinor et al., 2018). Moreover, climate change will affect FSN both directly and also indirectly through its impacts on other socioeconomic factors, such as health, peace and mobility, poverty, water security, changes in ecosystems and biodiversity, and infrastructure (O'Neill et al., 2022). Thus, multiple climate risks and multiple climate risk drivers can interact with each other, creating compound or cascading risks (Simpson et al., 2021). Conflicts in Yemen and Ethiopia combined with drought are resulting in an increased risk of famine, and extreme weather events combined with the current war in Ukraine have led to increased global food prices (Osendarp et al. 2022). As a result of non-climatic compounding risks to food security, Bezner Kerr et al. (2022) indicate that SDG 2 on Zero Hunger will likely not be met by 2030. For this reason, climate change risks to FSN cannot be considered in isolation from other sources of FSN risks. Adaptation options that target alleviating climate change risks to FSN also need to consider these other socioeconomic risks to FSN.

For example, climate risks to human health increase with greater exposure to excessive heat, reducing agricultural labor productivity and raising labor costs, increasing food prices (de Lima et al., 2021), and decreasing household income. Tropical cyclones and flooding, along with sea-level rise, increase risks to infrastructure, particularly in low-lying coastal regions (Koks et al., 2019), disrupting the livelihood of farmers and fishers, food storage and distribution, and thereby limiting food access. These cascading and/or compounding effects are already causing acute food insecurity in vulnerable regions, including southern Africa. They are, at least in part, attributable to human-induced climate change (Verschuur et al., 2021). These effects are projected to occur more frequently as global warming increases.

Risks to human health and food security can also be compounded by the climate change impacts on food safety. Warming will affect aquatic food security, nutrition and health in both marine and inland systems related to: increases in harmful algal blooms; higher incidence, severity and range expansion of pathogens such as *Vibrios*, and; increased bioaccumulation of pollutants such as methyl mercury (Colombo et al., 2020; FAO, 2020; Glibert, 2020; Griffith and Gobler, 2020; Mohamad et al., 2019). Higher temperatures and humidity can affect the growth and distribution of mycotoxins, increasing food and feed crop contamination and thereby risks to human and animal health.

While evidence of the implications of interacting risks is still developing, they may change the pattern of food security risk. For example, including the effect of heat stress on agricultural labour changes the global distribution of economic losses resulting from climate change on crop production (de Lima et al. 2021) – acknowledging that the effect of heat stress on labour is also caused by climate change, but is not usually considered when modelling crop production. It is possible more regions will reach thresholds of food insecurity sooner if the interactions with non-climatic risks are also considered. An improved understanding of these complex relationships is critical as effective adaptation will require a closer consideration of the combined effects of linked hazards (Lawrence et al., 2020).

4. Opportunities and limits to adaptation

Current evidence indicates that there are a range of adaptation approaches and options feasible and effective at reducing, but not eliminating, climate risks to FSN (Davis et al., 2021). In this regard, the impacts of climate change on FSN are expected to greatly vary by the levels of adaptation, changing contexts of vulnerability and warming levels. Increased adaptation can limit the worsening of food insecurity from climate change. Hasegawa et al. (2014) show that under RCP 2.6, the number of people at risk of hunger with adaptation (here, changes in crop variety and planting dates) are lower by 14, 22, and 39 million people for SSP1, SSP2, and SSP3, respectively, than without adaptation. Taking early and widespread transformational adaptation actions can help avoid or significantly lower the severity of risks of climate change to FSN (O'Neill et al., 2022; Davis et al., 2021). However, the limits to adaptation will expand at higher levels of global warming, necessitating actions toward the mitigation of greenhouse gases (GHG) (Bezner Kerr et al., 2022).

Adaptation options to prevent or reduce severe climate change risks to FSN seek to address the negative effects of climate change through the specific impact pathways shown in Fig. 1. Adaptation options against climate change risks to FSN range from farm-level actions to national and international policies (Bezner Kerr et al., 2022). Various adaptation options are available throughout food systems to lower the risks (Rosenzweig et al. 2020, Table 2). There are some adaptation options overarching all components of food systems, e.g. climate services, and integrated, multisectoral approaches which explicitly address vulnerable and marginalized groups (Bezner Kerr et al., 2022; Tirado et al., 2022).

There are many simulation studies which have tested crop management options, such as changing cultivars, changing planting dates, use of irrigation and water-saving irrigation methods. At a global average, crop-level adaptations are projected to offset the negative impacts of climate change on crop yields under 2 °C temperature rise (Challinor et al., 2014). Similarly, there are a large number of adaptation technologies proposed for terrestrial and aquatic livestock production, such as breeding for heat stress tolerance, species switching, shading and bathing of animals (Bezner Kerr et al., 2022). Adaptation options in the fisheries and aquaculture sectors include management (ecosystem-based, multi-species, dynamic), shared quotas and trade for equitable food provisioning, on-farm husbandry autonomous adaptations, early warning systems, technological developments and others (Bezner Kerr et al., 2022).

Increasing attention is being paid to ecosystem-based adaptation strategies, including crop diversification, application of agro-ecological practices and agroforestry, which reduce climate risk, support biodiversity and ecosystem services such as pollination and soil health (Bezner Kerr et al. 2022). Providing climate services, e.g., early warning systems, seasonal climate risk prediction, and crop insurance, also helps farmers adapt to climate change, lowering risks on FSN. Diversifying supply chains (O'Dwyer, 2020) and improving supply chains management would help alleviate climate change risks. These adaptation options include food storage, transport and distribution infrastructures, shortening and strengthening regional and local supply chains, urban agriculture, and reduced food loss. The options related to demand management, e.g. dietary changes and avoiding food waste, would also contribute to lower climate change risks to FSN. Besides food systems options, other adaptation options, e.g., generating off-farm incomes and migration, can help lower climate risks on FSN (Berrang-Ford et al., 2021; von Braun et al., 2021).

The very heterogeneous effects of climate change on food production worldwide and the increase in extreme weather events that temporally disrupt local food production activities, as well as associated concurrent shocks across food production systems in times of crises, highlight the importance of international and regional food trade within this volatile environment (Stevanović et al., 2016; Van Meijl et al., 2018).

The impacts of climate change on food systems are not experienced equally by all social groups (Mbow et al., 2019). Social inequities based on a range of factors, such as age, class, disability, ethnicity, gender, indigeneity, and race, among others, make some people more vulnerable than others, with differentiated capacities to adapt. To illustrate, peoples at a higher risk of seafood-related micronutrient deficiency risks are those in tropical and subtropical regions that are also regions likely to lose species through climate-induced poleward migrations of marine fish resources. It is increasingly understood that FSN also includes such critical dimensions as agency and sustainability (HLPE, 2020). Climate change-caused disruptions in the food value chains and food markets will affect the affordability of food and equity of access to food by vulnerable social groups often strongly interacting with other risks that these vulnerable populations are facing (Mbow et al., 2019). Actions to address social inequities and differential impacts of climate change risks on FSN imply, on the one hand, strengthening social protection and, on the other hand, empowering marginalized social groups through collective action. Assuring the equity of food access through social protection should not undermine people's agency,

Table 2

Correspondence of adaptation responses to each of the risk pathways in Fig. 1.

Adaptation responses	Food production	Food system-based livelihoods	Supply chain disruptions	Food quality and safety	Low nutrient content of crops	Changing disease and health environment
Integrated, multisectoral approaches	x	x	x	x	x	x
Dietary changes and reducing food waste	x		x	x	x	
Climate services	x	x	x			
Changes in crop varieties and planting dates	x	x	x	x	x	
Agroecological practices and crop diversification	x	x		x		
Improved irrigation methods	x	x				
Breeding for heat stress tolerance, species switching, shading and bathing of livestock	x	x				
Ecosystems-based fisheries management	x	x	x			
Diversifying and improving food supply chains and trade	x	x	x	x		
Strengthening social protection		x	x	x		
Increasing off-farm and non-farm income		x	x	x		x

Note: "x" marks map the correspondence of adaptation responses to each of the risk pathways.

but instead create enabling conditions for strengthening FSN agency of vulnerable populations by addressing underlying structural inequalities, including intra-household inequities in food distribution (Riley and Dodson 2014) and helping avoid maladaptive adaptation to FSN risks posed by climate change.

Multiple barriers to adaptation exist that may limit the implementation and effectiveness of adaptation options (Adger et al., 2009). Effective adaptation is more than a series of discrete options. Enabling conditions in the form of a continual process of learning, adjustment and planning are needed for successful adaptation along with massively increased investments towards adaptation. Flexible planning for the long-term, and the consideration of the implications of adaptation actions across multiple objectives will reduce the likelihood of maladaptive actions. Dynamic adaptive pathways may offer a way to identify and sequence adaptation options, allowing for the inherent uncertainty associated with climate projections (e.g. Cradock-Henry et al. (2020), Haasnoot et al., (2013)). However, adaptation strategies to date in general are often incremental, small-scale and single-sector focused. Transformative change is needed to reduce severe climate risks. Although, many adaptation options also have synergies with climate change mitigation and provide other co-benefits, e.g., improved livelihoods and health, energy and water security, and biodiversity conservation; however, some adaptation options can be maladaptive, i.e. increase vulnerabilities to climate change rather than decrease them (Bezner Kerr et al., 2022). Some mitigation responses to climate change may also undermine adaptive capacities. These aspects of adaptation options need to be carefully considered in their design and implementation.

5. Research gaps

There are a number of critical gaps in our understanding of the severity conditions of climate change risks to FSN. Here we highlight several key gaps for future research.

There have been virtually no studies projecting climate change risks to acute food insecurity, defined by IPC (2022), which is highly relevant to climate and weather extreme events that are projected to occur more frequently. This is limited by our capacity to project these extreme events and their impacts on food systems. The projections of severe climate change risks to FSN are still largely based on the climate change impacts on staple food crops, with still insufficient research on climate change impacts on other important crops (vegetables and fruits), livestock, aquaculture, and fisheries (Nelson et al., 2018; Mbow et al., 2019; Bezner Kerr et al., 2022). In particular, there is a significant lack of information on inland fisheries systems and aquaculture in low-income countries. Current food security risks assessments are still crop production-focused, and disruptions of other food security pillars such as access, utilization, and stability are much less studied, making it difficult to assess compounding and cascading risks and how these affect the severity of climate change risks to FSN (Davis et al., 2021). The impact projections often do not account for different levels of vulnerability among different groups.

Adaptation options in terrestrial climate change impact studies are often limited to a handful of options, mainly in production systems such as changing varieties, planting time, fertilizer, and irrigation management (Bezner Kerr et al., 2022). Feasibility and effectiveness assessments of adaptation options are limited, often lacking economic and institutional dimensions (Chichaibelu et al., 2021). For example, whilst there are national and international fisheries management bodies, currently considerations of climate change are rarely used in assessments and fishing allocations (Sumby et al., 2021). To envisage climate-resilient development pathways, we need a quantitative understanding of possible co-benefits and tradeoffs of adaptation options. Hence future research needs to provide us with clear answers identifying the most promising adaptation options to effectively address severe climate risk to food security.

Although many potential adaptation options will help reduce climate change risks to FSN, there is a lack of information on their costs and benefits over time and considering climate uncertainty. Such cost-benefit information, including consideration of the distributional effects of adaptation; assessment of the non-market and intangible benefits of adaptation; and the relative costs of action and inaction could increase the efficiency and targeting of adaptation policies (Bezner Kerr et al., 2022; Warner et al. 2021).

6. Conclusions

Future climate change is projected to exacerbate the magnitude and likelihood of adverse consequences to FSN. The timing of these impacts and our ability to respond to them varies based on the level of GHG emissions and SSPs. In this paper we define severe climate change risks to FSN as those which result, with high likelihood, in pervasive and persistent food insecurity and malnutrition for millions of people, have the potential for cascading effects beyond the food systems, and for which we have limited ability to prevent or fully respond; and propose to analyze it through severe risk of hunger and malnutrition. There are many practices, technologies, knowledge, institutional strategies and social processes to address these risks posed by climate change. The impacts of climate change on FSN would greatly vary by the levels of adaptation, changing contexts of vulnerability and warming levels. Current evidence indicates that there are a range of adaptation approaches and options which are feasible and effective at reducing, but not eliminating, climate risks to FSN. Taking early adaptation actions can help significantly lower the severity of risks of climate change to FSN.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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