Adaptation strategies/options	Systems	Benefits	Constraints or enablers	Confidence	Relevant sections
– **Effective linkage of freshwater aquatic food provisioning management to the adaptation plans of other water-using sectors, considering trade-offs of production with community nutritional needs**	Freshwater fisheries and aquaculture systems	– Reduce the risk of food insecurity and livelihood loss for those reliant on freshwater for inland fisheries and aquaculture	Changing precipitation patterns will increase competition for limited freshwater supplies	*Medium*	(5.8.4, 5.9.4.)
– **Agricultural production systems that integrate crops, livestock, forestry, fisheries and aquaculture**	Mixed system	– Increase food production per unit of land – Reduce climate risks – Reduce GHG emission – Confer buffering capacity – Increasing household resilience, though the benefits and challenges depend on local context	Uncertainties exist concerning the scalability of integrated systems; their uptake faces particular barriers around risk, land tenure, social inclusion, information and management skill, and the nature and timing of benefit flows	*High*	(5.10.4)
– **Investments in improved humidity and temperature control in storage facilities for perishable items, and changes in public policy that control international trade and domestic market transactions**	Post-harvest	– Improve food utilisation and access and thereby resilience to climate change	The extent to which adaptation activities beyond harvest are cost-effective, and the limits to such adaptation, are location-specific and largely unknown	*Medium*	(5.11.4)
– **Integrated multi-sectoral food system adaptation approaches that address food production, consumption and equity issues** – **Nutrition and gender-sensitive agriculture programmes, adaptive social protection and disaster risk management are examples**	Production and post-harvest	– Protect vulnerable groups against livelihood risks – Enhance responsiveness to extreme events	Differentiated responses based on food security level and climate risk can be effective	*Medium*	(5.12.4)
– **Rights-based approaches, including legislation, gender transformative approaches to agriculture, recognition of rights to land, seeds, fishing areas and other natural resources, and community-based adaptation**	Production and post-harvest	– Improved food security and nutrition for marginalised groups – Increased resilience through capacity-building of marginalised groups – Address questions of access to resources for marginalised groups	Focus on meaningful participation in governance, design and implementation of adaptation strategies of those groups who are vulnerable, including gender. Can be conflicts and trade-offs, such as between addressing land rights or traditional fishing grounds	*Medium*	(5.12.4)
– **Climate services**	Production	– Can support decision makers in agriculture by providing tailored information that can inform the implementation of specific adaptation options	For some high- and medium-income countries, evidence suggests that climate services have been underutilised. In low-income countries, use of climate services can increase yields and incomes and promote changes in farmers' practices, but *low confidence* that climate services are delivering on their potential, whether they are being accessed by the vulnerable, and how these services are contributing to food security and nutrition	*Medium*	(5.14.1)

Ecosystem-based adaptation, defined as the 'use of ecosystem management activities to increase the resilience and reduce the vulnerability of people and ecosystems to climate change' (Campbell et al., 2009), has at its core the recognition that there are unexploited synergies in agricultural systems that can increase productivity and resilience. These can result from increasing biodiversity, adding organic matter to soils, integrating livestock and aquatic species, including aquaculture, into farming practices, broadening landscape practices to exploit crop–forestry synergies, supporting beneficial insect populations and altering pest management practices that have unintended negative consequences. In addition, the chapter considers socioeconomic strategies to build resilience in the food system, strengthening local and regional economies, building on Indigenous and local knowledge, and addressing social inequity, through inclusive, participatory and democratic governance of food systems (HLPE, 2019; Wezel et al., 2020).

5.2 Observed Impacts and Key Risks

5.2.1 Detection and Attribution of Observed Impacts

Detection and attribution of climate change impacts on the food system remain challenging because many non-climate drivers are involved (Porter et al., 2014) but have been improved by recently developed climate model outputs tailored for impact attribution (Iizumi et al., 2018; Moore, 2020; Ortiz-Bobea et al., 2021).

Climate change has caused regionally different, but mostly negative, impacts on crop yields and quality and marketability of products (*high confidence*) (see Section 5.4.1 for observed impacts). There is *medium evidence* and *high agreement* that the effects of human-induced climate warming since the pre-industrial era has had significantly negative effects on global crop production, acting as a drag on the growth of agricultural production (Iizumi et al., 2018; Moore, 2020; Ortiz-Bobea et al., 2021). One global study using an empirical model estimated the negative effect of anthropogenic warming trends from 1961 to 2017 to be on average 5.3% for three staple crops (5.9% for maize, 4.9% for wheat and 4.2% for rice) (Moore, 2020). Another study using a process-based crop model found a yield loss of 4.1% (0.5–8.4%) for maize and 4.5% (0.5–8.4%) for soybean between 1981 and 2010 relative to the non-warming condition, even with CO_2 fertilisation effects (Iizumi et al., 2018). Human-induced warming trends since 1961 have also slowed down the growth of agricultural total factor productivity by 21% (Ortiz-Bobea et al., 2021). Regionally, heat and rainfall extremes intensified by human-induced warming in West Africa have reduced millet and sorghum yields by 10–20%, and 5–15%, respectively (Sultan et al., 2019).

Methane emissions significantly impact crop yields by increasing temperatures as a greenhouse gas (GHG) and surface ozone concentrations as a precursor (*medium confidence*) (Shindell, 2016; Van Dingenen, 2018; Shindell et al., 2019). Shindell (2016) estimated a net yield loss of 9.5±3.0% for four major crops due to anthropogenic emissions (1850–2010), after incorporation of the positive effect of CO_2 (6.5±1.0%) and the negative effects of warming (10.9±3.2%) and tropospheric ozone elevation (5.0±1.5%). Although these estimates were not linked with historical yield changes, more than half of the estimated yield loss is attributable to increasing temperature and ozone concentrations from methane emissions, suggesting the importance of methane mitigation in alleviating yield losses (*medium confidence*) (Section 5.4.1.4).

5

Climate change is already affecting livestock production (*high confidence)* (Section 5.5.1). The effects include direct impacts of heat stress on mortality and productivity, and indirect impacts have been observed on grassland quality, shifts in species distribution and range changes in livestock diseases (Sections 5.5.1.1–5.5.1.3). Quantitative assessment of observed impacts is still limited.

In aquatic systems, more evidence has accumulated since AR5 on warming-induced shifts (mainly poleward) of species (*high confidence*) (Section 5.8.1, Cross-Chapter Box MOVING PLATE this chapter), causing significant challenges for resource allocation between different countries and fishing fleets. Quantitative assessments of climate change impacts on production are still limited, but Free et al. (2019) estimated a 4.1% global loss of the maximum sustainable yield of several marine fish populations from 1930 to 2010 due to climate change. The effects of climate change on aquaculture are apparent but diverse, depending on the types and species of aquaculture (*high confidence*) (Section 5.9.1). Temperature increases, acidification, salt intrusion, oxygen deficiency, floods and droughts have negatively

Cascading impacts of climate hazards on food and nutrition

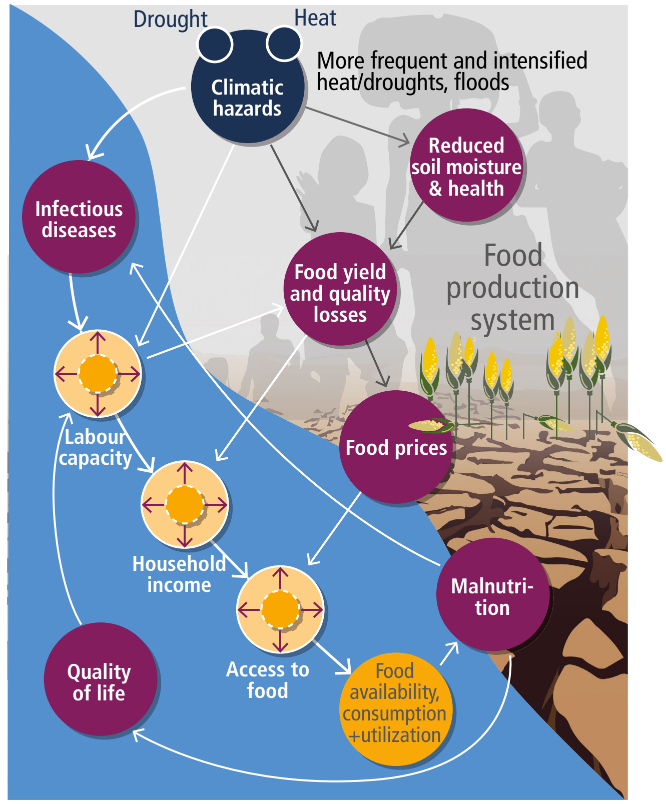

Figure 5.2 | Cascading impacts of climate hazards on food and nutrition. The factors involved the impacts on crop production and prices (black arrows) and interaction among food-health interaction (white arrows). Adapted and revised from (Phalkey et al., 2015).

impacted production via reduced growing suitability, mortalities or damages to infrastructure (Section 5.9.1).

The impacts of climate change on food provisioning have cascading effects on key elements of food security, such as food prices, household income, food safety and nutrition of vulnerable groups (Peri, 2017; Ubilava, 2018; 5.11, 5.12). Climate extreme events are frequently causing acute food insecurity (Section 5.12.3, FSIN, 2021). There is growing evidence that human-induced climate warming has amplified climate extreme events (Seneviratne et al., 2021), but detection and attribution of food insecurity to anthropogenic climate change is still limited by a lack of long-term data and complexity of food systems (Phalkey et al., 2015; Cooper et al., 2019). A recent event attribution study by Funk (2018) demonstrated that anthropogenic enhancement of the 2015/2016 El Niño increased drought-induced crop production losses in Southern Africa. Human-induced warming also exacerbated the 2007 drought in southern Africa, causing food shortages, price spikes and acute food insecurity in Lesotho (Verschuur et al., 2021).

5.2.2 Key Risks

Key risks in this chapter are grouped into those related to food security, food safety and dietary health, livelihoods of people in related sectors and ecosystem services (Table 16.9). Determining when a risk is considered severe is challenging to quantify because of the complexity of the food system, uncertainty about the effects and ethical challenges.

Current levels of food insecurity are already high in some parts of the world, and often exacerbated by short-term food shortages and price spikes caused by weather extremes partly linked to climate change (Sections 5.2.1, 5.12.3, 16.5.2). Climate change will increase malnourished populations through direct impacts on food production and have cascading impacts on food prices and household incomes, all of which will reduce access to safe and nutritious food (*high confidence)* (Figure 5.2, 5.12).

Extreme climate events will become more frequent and force some of the current food production areas beyond the safe climatic space for production (*high confidence*) (Sections 5.4.3, 5.5.2). Globally, 10% of the currently suitable area for major crops and livestock is projected to be climatically unsuitable in mid-century and 31–34% by the end of the century under SSP5-8.5 (Kummu et al., 2021). Adverse effects of climate change on food production will become more severe when global temperatures rise by more than 2°C (Sections 5.4.4.1, 5.12.4.1). One study estimated that the heat stress from projected 3°C warming above baseline (1986–2005) would reduce labour capacity by 30–50% in Sub-Saharan Africa and Southeast Asia, leading to a 5% increase in crop prices because of higher labour cost and production losses, thereby undermining food availability, access and livelihood (de Lima et al., 2021). Thiault et al. (2019) projected that, by 2100, climate change under RCP8.5 could have negative impacts on both agriculture and marine fisheries productivity in countries where 90% of the world population live. A global analysis of shellfish aquaculture estimated that habitat suitability will decline beyond 2060 globally, but much sooner in some Asian countries (Stewart-Sinclair et al., 2020; 5.9.1). These negative effects in the second half of the century will be much less under RCP2.6.

Climate change impacts will increase the number of people at risk of hunger, in 2050 ranging from 8 million people under SSP1 to 80 million people under SSP3 scenarios (RCP6.0), compared with a world with no climate change (Mbow et al., 2019). Estimates also vary depending on the adaptation and mitigation assumptions (Hasegawa et al., 2018; Janssens et al., 2020). Geographically, nearly 80% of the population at risk of hunger are projected to reside in Africa and Asia (Nelson et al., 2018). Projections of risk of hunger beyond 2050 are limited, but it will grow from the mid-century towards the end of the century, with more people at risk under RCP8.5 compared with RCP4.5 (Richardson et al., 2018). Regional disparity is projected to increase, particularly under a high-emission scenario.

Climate change will increase the costs and management challenges of providing safe food. The safety challenges arise from contamination caused by increased prevalence of pathogens, HAB and toxic inorganic bioaccumulation (*high confidence*) (Sections 5.8, 5.9, 5.11, 5.12). Micronutrient deficiency is prevalent across many regions and will continue to be a problem at least during the first half of the century (Nelson et al., 2018), with significant implications for human health (Section 5.12.4).

Food security and healthy balanced diets will also be undermined by reduced livelihoods and health of people in agriculture and food-related sectors (Sections 5.12.3, 5.12.4), diminished ecosystem services provided by pollinators, the soil biome (Section 5.4.3) and water systems, and climate-mitigation related policies that solely focus on reducing GHG emissions without considering their potential to increase competition with food production for scarce land and water (Section 5.13.3).

5.3 Methodologies and Associated Uncertainties

Chapter text draws on previous IPCC reports, other reports (i.e., High Level Panel of Experts (HLPE), Food and Agriculture Organization (FAO), and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)), and literature published since 2014. This section highlights key trends in research topics and methods since AR5.

5.3.1 Methodologies for Assessing Impacts and Risks

Since AR5, there are more examples of observed impacts from past climate change in cropping systems (Section 5.4.1), pastoral systems (Section 5.5.1), forests (Section 5.6.1), fisheries (Section 5.8.1) and mixed farming systems (Section 5.10.1). These assessments of observed impacts make use of historical data on climate, production area and yield to attribute the role of climate in driving changes in suitability, production, yield, food quality or total factor productivity (Ortiz-Bobea et al., 2021). Observations across the global food systems have been analysed (Cottrell et al., 2019), with the advantage that unexpected impacts due to changes in seasonality and biotic interactions can be detected. Quantitative analysis is only possible in places with adequate historical data; in many cases, studies rely on qualitative assessments, often drawing on farmers' perceptions of climate impacts.

Projecting future climate impacts relies on modelling that combines climate data with data from experimental studies testing how species respond to each climate factor. In cropping and forest systems, a network of experimental studies with plants exposed to elevated CO_2 concentrations, ozone and elevated temperature provides data on the fundamental responses to climate and atmospheric conditions (i.e., free-air carbon dioxide enrichment (FACE) and temperature free-air controlled enhancement (T-FACE) systems). FACE results have been combined and assessed more extensively since AR5 (Bishop et al., 2014; Haworth et al., 2016; Kimball, 2016; Ainsworth and Long, 2021). Field-based FACE studies have several advantages over more enclosed testing chambers, although results from more controlled experiments and coordination between different methods continue to give new insights into crop responses to climate change and variability (Drag et al., 2020; Ainsworth and Long, 2021; Sun et al., 2021). Experimental results have limitations and can be difficult to scale up (Porter