5

Food security

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Executive summary

The current food system (production, transport, processing, packaging, storage, retail, consumption, loss and waste) feeds the great majority of world population and supports the livelihoods of over 1 billion people. Since 1961, food supply per capita has increased more than 30%, accompanied by greater use of nitrogen fertilisers (increase of about 800%) and water resources for irrigation (increase of more than 100%). However, an estimated 821 million people are currently undernourished, 151 million children under five are stunted, 613 million women and girls aged 15 to 49 suffer from iron deficiency, and 2 billion adults are overweight or obese. The food system is under pressure from non-climate stressors (e.g., population and income growth, demand for animal-sourced products), and from climate change. These climate and non-climate stresses are impacting the four pillars of food security (availability, access, utilisation, and stability). {5.1.1, 5.1.2}

Observed climate change is already affecting food security through increasing temperatures, changing precipitation patterns, and greater frequency of some extreme events (*high confidence*). Studies that separate out climate change from other factors affecting crop yields have shown that yields of some crops (e.g., maize and wheat) in many lower-latitude regions have been affected negatively by observed climate changes, while in many higher-latitude regions, yields of some crops (e.g., maize, wheat, and sugar beets) have been affected positively over recent decades. Warming compounded by drying has caused large negative effects on yields in parts of the Mediterranean. Based on indigenous and local knowledge (ILK), climate change is affecting food security in drylands, particularly those in Africa, and high mountain regions of Asia and South America. {5.2.2}

Food security will be increasingly affected by projected future climate change (*high confidence*). Across Shared Socio-economic Pathways (SSPs) 1, 2, and 3, global crop and economic models projected a 1–29% cereal price increase in 2050 due to climate change (RCP 6.0), which would impact consumers globally through higher food prices; regional effects will vary (*high confidence*). Low-income consumers are particularly at risk, with models projecting increases of 1–183 million additional people at risk of hunger across the SSPs compared to a no climate change scenario (*high confidence*). While increased CO_2 is projected to be beneficial for crop productivity at lower temperature increases, it is projected to lower nutritional quality (*high confidence*) (e.g., wheat grown at 546–586 ppm CO_2 has 5.9–12.7% less protein, 3.7–6.5% less zinc, and 5.2–7.5% less iron). Distributions of pests and diseases will change, affecting production negatively in many regions (*high confidence*). Given increasing extreme events and interconnectedness, risks of food system disruptions are growing (*high confidence*). {5.2.3, 5.2.4}

Vulnerability of pastoral systems to climate change is very high (*high confidence*). Pastoralism is practiced in more than 75% of countries by between 200 and 500 million people, including nomadic communities, transhumant herders, and agropastoralists. Impacts in pastoral systems in Africa include lower pasture and animal productivity, damaged reproductive function, and biodiversity loss. Pastoral system vulnerability is exacerbated by non-climate factors (land tenure, sedentarisation, changes in traditional institutions, invasive species, lack of markets, and conflicts). {5.2.2}

Fruit and vegetable production, a key component of healthy diets, is also vulnerable to climate change *(medium evidence, high agreement)*. Declines in yields and crop suitability are projected under higher temperatures, especially in tropical and semi-tropical regions. Heat stress reduces fruit set and speeds up development of annual vegetables, resulting in yield losses, impaired product quality, and increasing food loss and waste. Longer growing seasons enable a greater number of plantings to be cultivated and can contribute to greater annual yields. However, some fruits and vegetables need a period of cold accumulation to produce a viable harvest, and warmer winters may constitute a risk. {5.2.2}

Food security and climate change have strong gender and equity dimensions (*high confidence*). Worldwide, women play a key role in food security, although regional differences exist. Climate change impacts vary among diverse social groups depending on age, ethnicity, gender, wealth, and class. Climate extremes have immediate and long-term impacts on livelihoods of poor and vulnerable communities, contributing to greater risks of food insecurity that can be a stress multiplier for internal and external migration (*medium confidence*). {5.2.6} Empowering women and rights-based approaches to decision-making can create synergies among household food security, adaptation, and mitigation. {5.6.4}

Many practices can be optimised and scaled up to advance adaptation throughout the food system (*high confidence*). Supply-side options include increased soil organic matter and erosion control, improved cropland, livestock, grazing land management, and genetic improvements for tolerance to heat and drought. Diversification in the food system (e.g., implementation of integrated production systems, broad-based genetic resources, and heterogeneous diets) is a key strategy to reduce risks (*medium confidence*). Demand-side adaptation, such as adoption of healthy and sustainable diets, in conjunction with reduction in food loss and waste, can contribute to adaptation through reduction in additional land area needed for food production and associated food system vulnerabilities. ILK can contribute to enhancing food system resilience (*high confidence*). {5.3, 5.6.3 Cross-Chapter Box 6 in Chapter 5}

About 21–37% of total greenhouse gas (GHG) emissions are attributable to the food system. These are from agriculture and land use, storage, transport, packaging, processing, retail, and consumption (*medium confidence*). This estimate includes emissions of 9–14% from crop and livestock activities within the farm gate and 5–14% from land use and land-use change including deforestation and peatland degradation (*high confidence*); 5–10% is from supply chain activities (*medium confidence*). This estimate includes GHG emissions from food loss and waste. Within the food system, during the period 2007–2016, the major sources of emissions from the supply side were agricultural production, with crop and livestock activities within the farm gate generating respectively 142 ± 42 $TgCH_4$ yr^{-1} (*high confidence*) and 8.0 ± 2.5 TgN_2O yr^{-1} (*high confidence*), and CO_2 emissions linked to relevant land-use change dynamics such as deforestation and peatland degradation, generating 4.9 ± 2.5 $GtCO_2$ yr^{-1}. Using 100-year GWP values (no climate feedback) from the IPCC AR5, this implies that total GHG emissions from agriculture were 6.2 ± 1.4 $GtCO_2$-eq yr^{-1}, increasing to 11.1 ± 2.9 $GtCO_2$-eq yr^{-1} including relevant land use. Without intervention, these are likely to increase by about 30–40% by 2050, due to increasing demand based on population and income growth and dietary change (*high confidence*). {5.4}

Supply-side practices can contribute to climate change mitigation by reducing crop and livestock emissions, sequestering carbon in soils and biomass, and by decreasing emissions intensity within sustainable production systems (*high confidence*). Total technical mitigation potential from crop and livestock activities and agroforestry is estimated as 2.3–9.6 GtCO2-eq yr^{-1} by 2050 (*medium confidence*). Options with large potential for GHG mitigation in cropping systems include soil carbon sequestration (at decreasing rates over time), reductions in N_2O emissions from fertilisers, reductions in CH_4 emissions from paddy rice, and bridging of yield gaps. Options with large potential for mitigation in livestock systems include better grazing land management, with increased net primary production and soil carbon stocks, improved manure management, and higher-quality feed. Reductions in GHG emissions intensity (emissions per unit product) from livestock can support reductions in absolute emissions, provided appropriate governance to limit total production is implemented at the same time (*medium confidence*). {5.5.1}

Consumption of healthy and sustainable diets presents major opportunities for reducing GHG emissions from food systems and improving health outcomes (*high confidence*). Examples of healthy and sustainable diets are high in coarse grains, pulses, fruits and vegetables, and nuts and seeds; low in energy-intensive animal-sourced and discretionary foods (such as sugary beverages); and with a carbohydrate threshold. Total technical mitigation potential of dietary changes is estimated as 0.7–8.0 $GtCO_2$-eq yr^{-1} by 2050 (*medium confidence*). This estimate includes reductions in emissions from livestock and soil carbon sequestration on spared land, but co-benefits with health are not taken into account. Mitigation potential of dietary change may be higher, but achievement of this potential at broad scales depends on consumer choices and dietary preferences that are guided by social, cultural, environmental, and traditional factors, as well as income growth. Meat analogues such as imitation meat (from plant products), cultured meat, and insects may help in the transition to more healthy and sustainable diets, although their carbon footprints and acceptability are uncertain. {5.5.2, 5.6.5}

Reduction of food loss and waste could lower GHG emissions and improve food security (*medium confidence*). Combined food loss and waste amount to 25–30% of total food produced (*medium confidence*). During 2010–2016, global food loss and waste equalled 8–10% of total anthropogenic GHG emissions (*medium confidence*); and cost about 1 trillion USD2012 per year (*low confidence*). Technical options for reduction of food loss and waste include improved harvesting techniques, on-farm storage, infrastructure, and packaging. Causes of food loss (e.g., lack of refrigeration) and waste (e.g., behaviour) differ substantially in developed and developing countries, as well as across regions *(robust evidence, medium agreement)*. {5.5.2}

Agriculture and the food system are key to global climate change responses. Combining supply-side actions such as efficient production, transport, and processing with demand-side interventions such as modification of food choices, and reduction of food loss and waste, reduces GHG emissions and enhances food system resilience (*high confidence*). Such combined measures can enable the implementation of large-scale land-based adaptation and mitigation strategies without threatening food security from increased competition for land for food production and higher food prices. Without combined food system measures in farm management, supply chains, and demand, adverse effects would include increased numbers of malnourished people and impacts on smallholder farmers (*medium evidence*, *high agreement*). Just transitions are needed to address these effects. {5.5, 5.6, 5.7}

For adaptation and mitigation throughout the food system, enabling conditions need to be created through policies, markets, institutions, and governance (*high confidence*). For adaptation, resilience to increasing extreme events can be accomplished through risk sharing and transfer mechanisms such as insurance markets and index-based weather insurance (*high confidence*). Public health policies to improve nutrition – such as school procurement, health insurance incentives, and awareness-raising campaigns – can potentially change demand, reduce healthcare costs, and contribute to lower GHG emissions (*limited evidence*, *high agreement*). Without inclusion of comprehensive food system responses in broader climate change policies, the mitigation and adaptation potentials assessed in this chapter will not be realised and food security will be jeopardised (*high confidence*). {5.7, 5.8}

5.1 Framing and context

The current food system (production, transport, processing, packaging, storage, retail, consumption, loss and waste) feeds the great majority of world population and supports the livelihoods of over 1 billion people. Agriculture as an economic activity generates between 1% and 60% of national GDP in many countries, with a world average of about 4% in 2017 (World Bank 2019). Since 1961, food supply per capita has increased more than 30%, accompanied by greater use of nitrogen fertiliser (increase of about 800%) and water resources for irrigation (increase of more than 100%).

The rapid growth in agricultural productivity since the 1960s has underpinned the development of the current global food system that is both a major driver of climate change, and increasingly vulnerable to it (from production, transport, and market activities). Given the current food system, the UN Food and Agriculture Organization (FAO) estimates that there is a need to produce about 50% more food by 2050 in order to feed the increasing world population (FAO 2018a). This would engender significant increases in GHG emissions and other environmental impacts, including loss of biodiversity. FAO (2018a) projects that by 2050 cropland area will increase 90–325 Mha, between 6% and 21% more than the 1567 Mha cropland area of 2010, depending on climate change scenario and development pathway (the lowest increase arises from reduced food loss and waste and adoption of more sustainable diets).

Climate change has direct impacts on food systems, food security, and, through the need to mitigate, potentially increases the competition for resources needed for agriculture. Responding to climate change through deployment of land-based technologies for negative emissions based on biomass production would increasingly put pressure on food production and food security through potential competition for land.

Using a food system approach, this chapter addresses how climate change affects food security, including nutrition, the options for the food system to adapt and mitigate, synergies and trade-offs among these options, and enabling conditions for their adoption. The chapter assesses the role of incremental and transformational adaptation, and the potential for combinations of supply-side measures such as sustainable intensification (increasing productivity per hectare) and demand-side measures (e.g., dietary change and waste reduction) to contribute to climate change mitigation.

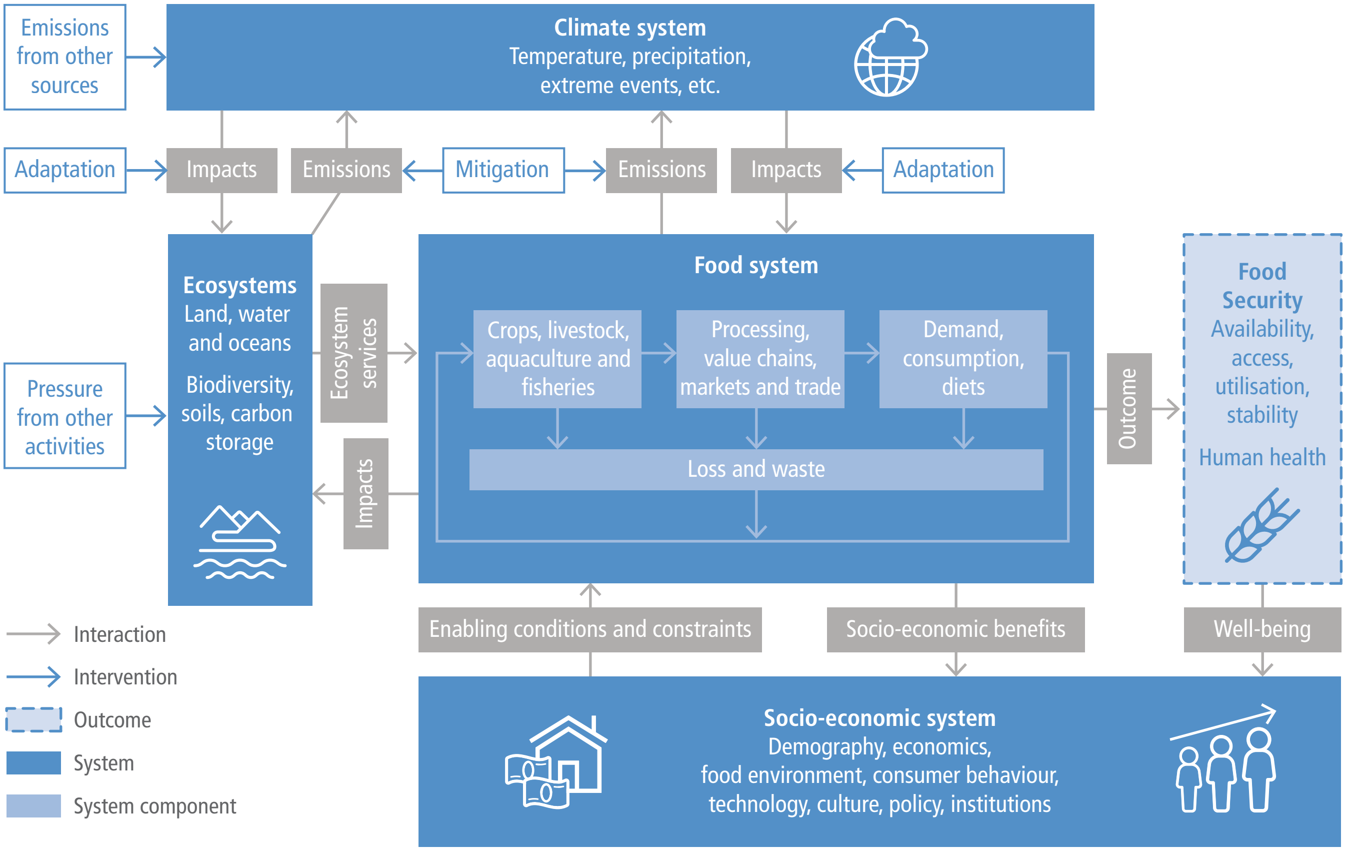

Figure 5.1 | Interlinkages between the climate system, food system, ecosystems (land, water and oceans) and socio-economic system. These systems operate at multiple scales, both global and regional. Food security is an outcome of the food system leading to human well-being, which is also indirectly linked with climate and ecosystems through the socio-economic system. Adaptation measures can help to reduce negative impacts of climate change on the food system and ecosystems. Mitigation measures can reduce GHG emissions coming from the food system and ecosystems.

5.1.1 Food security and insecurity, the food system and climate change

The **food system** encompasses all the activities and actors in the production, transport, manufacturing, retailing, consumption, and waste of food, and their impacts on nutrition, health and well-being, and the environment (Figure 5.1).

5.1.1.1 Food security as an outcome of the food system

The activities and the actors in the food system lead to outcomes such as food security and generate impacts on the environment. As part of the environmental impacts, food systems are a considerable contributor to GHG emissions, and thus climate change (Section 5.4). In turn, climate change has complex interactions with food systems, leading to food insecurity through impacts on food availability, access, utilisation and stability (Table 5.1 and Section 5.2).

We take a **food systems lens** in the Special Report on Climate Change and Land (SRCCL) to recognise that demand for and supply of food are interlinked and need to be jointly assessed in order to identify the challenges of mitigation and adaptation to climate change. Outcomes cannot be disaggregated solely to, for example, agricultural production, because the demand for food shapes what is grown, where it is grown, and how much is grown. Thus, GHG emissions from agriculture result, in large part, from 'pull' from the demand side. Mitigation and adaptation involve modifying production, supply chain, and demand practices (through, for example, dietary choices, market incentives, and trade relationships), so as to evolve to a more sustainable and healthy food system.

According to FAO (2001a), **food security** is 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. 'All people at all times' implies the need for equitable and stable food distribution, but it is increasingly recognised that it also covers the need for inter-generational equity, and therefore 'sustainability' in food production. 'Safe and nutritious food … for a healthy life' implies that food insecurity can occur if the diet is not nutritious, including when there is consumption of an excess of calories, or if food is not safe, meaning free from harmful substances.

A prime impact of food insecurity is **malnourishment** (literally 'bad nourishment') leading to **malnutrition**, which refers to deficiencies, excesses, or imbalances in a person's intake of energy and/or nutrients. As defined by FAO et al. (2018), undernourishment occurs when an individual's habitual food consumption is insufficient to provide the amount of dietary energy required to maintain a normal, active, healthy life. In addition to undernourishment in the sense of insufficient calories ('hunger'), undernourishment occurs in terms of nutritional deficiencies in vitamins (e.g., vitamin A) and minerals (e.g., iron, zinc, iodine), so-called 'hidden hunger'. Hidden hunger tends to be present in countries with high levels of undernourishment (Muthayya et al. 2013), but micronutrient deficiency can occur in societies with low prevalence of undernourishment. For example, in many parts of the world teenage girls suffer from iron deficiency (Whitfield et al. 2015) and calcium deficiency is common in Western-style diets (Aslam and Varani 2016). Food security is related to nutrition, and conversely food insecurity is related to malnutrition. Not all malnourishment arises from food insecurity, as households may have access to healthy diets but choose to eat unhealthily, or it may arise from illness. However, in many parts of the world, poverty is linked to poor diets (FAO et al. 2018). This may be through lack of resources to produce or access food in general, or healthy food, in particular, as healthier diets are more expensive than diets rich in calories but poor in nutrition *(high confidence*) (see meta-analysis by Darmon and Drewnowski 2015). The relationship between poverty and poor diets may also be linked to unhealthy 'food environments,' with retail outlets in a locality only providing access to foods of low nutritional quality (Gamba et al. 2015) – such areas are sometimes termed 'food deserts' (Battersby 2012).

Whilst conceptually the definition of food security is clear, it is not straightforward to measure in a simple way that encompasses all its aspects. Although there are a range of methods to assess food insecurity, they all have some shortcomings. For example, the FAO has developed the Food Insecurity Experience Scale (FIES), a survey-based tool to measure the severity of overall households' inability to access food. While it provides reliable estimates of the prevalence of food insecurity in a population, it does not reveal whether actual diets are adequate or not with respect to all aspects of nutrition (Section 5.1.2.1).

5.1.1.2 Effects of climate change on food security

Climate change is projected to negatively impact the four pillars of food security – availability, access, utilisation and stability – and their interactions (FAO et al. 2018) (*high confidence*). This chapter assesses recent work since AR5 that has strengthened understanding of how climate change affects each of these pillars across the full range of food system activities (Table 5.1 and Section 5.2).

While most studies continue to focus on availability via impacts on food production, more studies are addressing related issues of access (e.g., impacts on food prices), utilisation (e.g., impacts on nutritional quality), and stability (e.g., impacts of increasing extreme events) as they are affected by a changing climate (Bailey et al. 2015). Low-income producers and consumers are likely to be most affected because of a lack of resources to invest in adaptation and diversification measures (UNCCD 2017; Bailey et al. 2015).

Table 5.1 | Relationships between food security, the food system, and climate change, and guide to chapter.

Food security pillar	Examples of observed and projected climate change impacts	Sections	Examples of adaptation and mitigation	Section
Availability *Production of food and its readiness for use through storage, processing, distribution, sale and/or exchange*	Reduced yields in crop and livestock systems	5.2.2.1, 5.2.2.2	Development of adaptation practices	5.3
	Reduced yields from lack of pollinators; pests and diseases	5.2.2.3, 5.2.2.4	Adoption of new technologies, new and neglected varieties	5.3.2.3, 5.3.3.1,
	Reduced food quality affecting availability (e.g., food spoilage and loss from mycotoxins)	5.2.4.1, 5.5.2.5	Enhanced resilience by integrated practices, better food storage	5.3.2.3, 5.3.3.4, 5.6.4
	Disruptions to food storage and transport networks from change in climate, including extremes	5.2.5.1, 5.3.3.4, 5.8.1, Box 5.5	Reduction of food demand by reducing waste, modifying diets	5.3.4, 5.5.2, 5.7
			Closing of crop yield and livestock productivity gaps	5.6.4.4, 5.7
			Risk management, including marketing mechanisms, financial insurance	5.3.2, 5.7
Access *Ability to obtain food, including effects of price*	Yield reductions, changes in farmer livelihoods, limitations on ability to purchase food	5.2.2.1, 5.2.2.2	Integrated agricultural practices to build resilient livelihoods	5.6.4
	Price rise and spike effects on low-income consumers, in particular women and children, due to lack of resources to purchase food	5.1.3, 5.2.3.1, 5.2.5.1, Box 5.1	Increased supply chain efficiency (e.g., reducing loss and waste)	5.3.3, 5.3.4
	Effects of increased extreme events on food supplies, disruption of agricultural trade and transportation infrastructure	5.8.1	More climate-resilient food systems, shortened supply chains, dietary change, market change	5.7
Utilisation *Achievement of food potential through nutrition, cooking, health*	Impacts on food safety due to increased prevalence of microorganisms and toxins	5.2.4.1	Improved storage and cold chains	5.3.3, 5.3.4
	Decline in nutritional quality resulting from increasing atmospheric CO_2	5.2.4.2	Adaptive crop and livestock varieties, healthy diets, better sanitation	5.3.4, 5.5.2, 5.7
	Increased exposure to diarrheal and other infectious diseases due to increased risk of flooding	5.2.4.1		
Stability *Continuous availability and access to food without disruption*	Greater instability of supply due to increased frequency and severity of extreme events; food price rises and spikes; instability of agricultural incomes	5.2.5, 5.8.1	Resilience via integrated systems and practices, diversified local agriculture, infrastructure investments, modifying markets and trade, reducing food loss and waste	5.6.4, 5.7, 5.8.1
	Widespread crop failure contributing to migration and conflict	5.8.2	Crop insurance for farmers to cope with extreme events	5.3.2.2, 5.7
			Capacity building to develop resilient systems	5.3.6, 5.7.4
Combined *Systemic impacts from interactions of all four pillars*	Increasing undernourishment as food system is impacted by climate change	5.1	Increased food system productivity and efficiency (e.g., supply side mitigation, reducing waste, dietary change)	5.5.1, 5.7
	Increasing obesity and ill health through narrow focus on adapting limited number of commodity crops	5.1	Increased production of healthy food and reduced consumption of energy-intensive products	5.5.2, 5.7
	Increasing environmental degradation and GHG emissions	Cross-Chapter Box 6	Development of climate smart food systems by reducing GHG emissions, building resilience, adapting to climate change	5.3.3, 5.7
	Increasing food insecurity due to competition for land and natural resources (e.g., for land-based mitigation)	5.6.1	Governance and institutional responses (including food aid) that take into consideration gender and equity.	5.2.5, 5.7

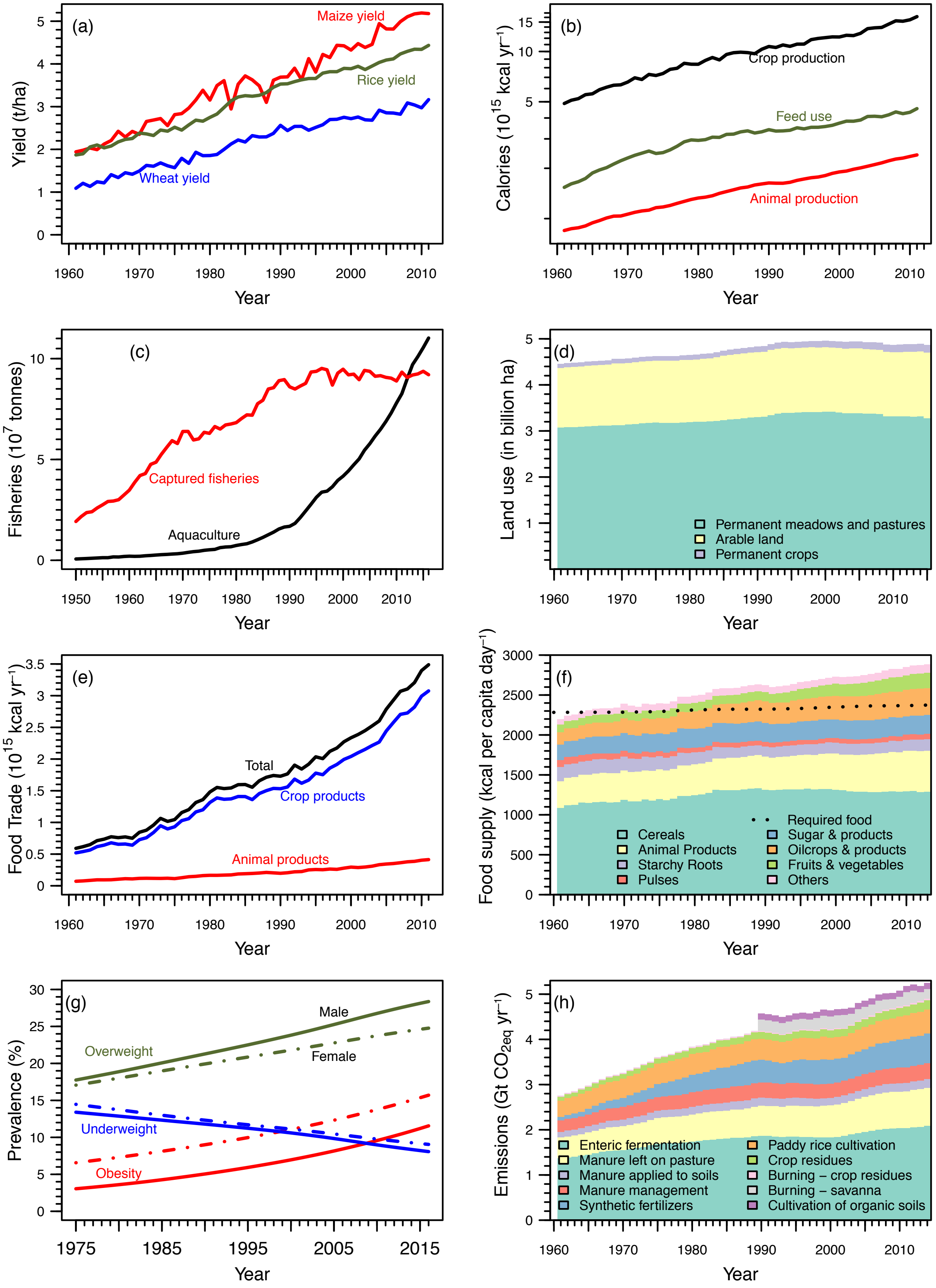

Figure 5.2 | Global trends in (a) yields of maize, rice, and wheat (FAOSTAT 2018) – the top three crops grown in the world; **(b)** production of crop and animal calories and use of crop calories as livestock feed (FAOSTAT 2018); **(c)** production from marine and aquaculture fisheries (FishStat 2019); **(d)** land used for agriculture (FAOSTAT 2018); **(e)** food trade in calories (FAOSTAT 2018); **(f)** food supply and required food (i.e., based on human energy requirements for medium physical activities) from 1961–2012 (FAOSTAT 2018; Hiç et al. 2016); **(g)** prevalence of overweight, obesity and underweight from 1975–2015 (Abarca-Gómez et al. 2017); and **(h)** GHG emissions for the agriculture sector, excluding land-use change (FAOSTAT 2018). For figures (b) and (e), data provided in mass units were converted into calories using nutritive factors (FAO 2001b). Data on emissions due to burning of savanna and cultivation of organic soils is provided only after 1990 (FAOSTAT 2018).

5.1.2 Status of the food system, food insecurity and malnourishment

5.1.2.1 Trends in the global food system

Food is predominantly produced on land, with, on average, 83% of the 697 kg of food consumed per person per year, 93% of the 2884 kcal per day, and 80% of the 81 g of protein eaten per day coming from terrestrial production in 2013 (FAOSTAT 2018).[1] With increases in crop yields and production (Figure 5.2), the absolute supply of food has been increasing over the last five decades. Growth in production of animal-sourced food is driving crop utilisation for livestock feed (FAOSTAT 2018; Pradhan et al. 2013a). Global trade of crop and animal-sourced food has increased by around 5 times between 1961 and 2013 (FAOSTAT 2018). During this period, global food availability has increased from 2200 kcal/cap/day to 2884 kcal/cap/day, making a transition from a food deficit to a food surplus situation (FAOSTAT 2018; Hiç et al. 2016).

The availability of cereals, animal products, oil crops, and fruits and vegetables has mainly grown (FAOSTAT 2018), reflecting shifts towards more affluent diets. This, in general, has resulted in a decrease in prevalence of underweight and an increase in prevalence of overweight and obesity among adults (Abarca-Gómez et al. 2017). During the period 1961–2016, anthropogenic GHG emissions associated with agricultural production has grown from 3.1 GtCO2-eq yr^{-1} to 5.8 GtCO$_2$-eq yr^{-1} (Section 5.4.2 and Chapter 2). The increase in emissions is mainly from the livestock sector (from enteric fermentation and manure left on pasture), use of synthetic fertiliser, and rice cultivation (FAOSTAT 2018).

5.1.2.2 Food insecurity status and trends

In addressing food security the dual aspects of malnutrition – under-nutrition and micro-nutrient deficiency, as well as over-consumption, overweight, and obesity – need to be considered (Figure 5.2 (g) and Table 5.2). The UN agencies' State of Food Security and Nutrition 2018 report (FAO et al. 2018) and the Global Nutrition Report 2017 (Development Initiatives 2017) summarise the global data. The *State of Food Security* report's estimate for undernourished people on a global basis is 821 million, up from 815 million the previous year and 784 million the year before that. Previous to 2014/2015 the prevalence of hunger had been declining over the last three decades. The proportion of young children (under five) who are stunted (low height-for-age), has been gradually declining, and was 22% in 2017 compared to 31% in 2012 (150.8 million, down from 165.2 million in 2012). In 2017, 50.5 million children (7.5%) under five were wasted (low weight-for-height). Since 2014, undernutrition has worsened, particularly in parts of Sub-Saharan Africa, south-eastern Asia and Western Asia, and recently Latin America. Deteriorations have been observed most notably in situations of conflict and conflict combined with droughts or floods (FAO et al. 2018).

Regarding micronutrient deficiencies known as 'hidden hunger', reporting suggests a prevalence of one in three people globally (FAO 2013a; von Grebmer et al. 2014; Tulchinsky 2010) (Table 5.2). In the last decades, hidden hunger (measured through proxies targeting iron, vitamin A, and zinc deficiencies) worsened in Africa, while it mainly improved in the Asia and Pacific regions (Ruel-Bergeron et al. 2015). In 2016, 613 million women and girls aged 15 to 49 suffered from iron deficiency (Development Initiatives 2018); in 2013, 28.5%

Table 5.2 | Global prevalence of various forms of malnutrition.

	HLPE 2017 (UN)	SOFI 2017 (FAO)	GNR 2017	SOFI 2018 (FAO)	GNR2018
Overweight but not obese[a]	1.3 billion		1.29 billion		1.34 billion (38,9%)[c]
Overweight under five	41 million	41 million	41 million	38 million	38 million
Obesity[b]	600 million	600 million (13%)	641 million	672 million	678 million (13,1%)[c]
Undernourishment	800 million	815 million	815 million	821 million	
Stunting under five	155 million	155 million	155 million[d]	151 million	151 million[d] (22%)
Wasting under five	52 million	52 million (8%)	52 million[d]	50 million	51 million[d] (7%)
MND (iron)	19.2% of pregnant women[e]	33% women of reproductive age	613 million women and girls aged 15 to 49[f]	613 million (32.8%) women and girls aged 15 to 49[f]	613 million (32.8%) women and girls aged 15 to 49[f]

HLPE: High Level Panel of Experts on Food Security and Nutrition; SOFI: The State of Food Security and Nutrition in the World; GNR: Global Nutrition Report; MND: Micro nutrient deficiency (iron deficiency for year 2016, uses anaemia as a proxy (percentage of pregnant women whose haemoglobin level is less than 110 grams per litre at sea level and percentage of non-pregnant women whose haemoglobin level is less than 120 grams per litre at sea level).

[a] Body mass index between 25 kg m^{-2} and 29.9 kg m^{-2}.

[b] Body mass index greater than 30 kg m^{-2}.

[c] Prevalence of overweight/obesity among adults (age ≥18) in year 2016. Data from NCD Risc data source.

[d] UNICEF WHO Joint Malnutrition.

[e] In 2011.

[f] Anaemia prevalence in girls and women aged 15 to 49.

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[1] Does not take into account terrestrial production of feed.

of the global population suffered from iodine deficiency; and in 2005, 33.3% of children under five and 15.3% of pregnant women suffered from vitamin A deficiency, and 17.3% of the global population suffered from zinc deficiency (HLPE 2017).

Globally, as the availability of inexpensive calories from commodity crops increases, so does per capita consumption of calorie-dense foods (Ng et al. 2014; NCD-RisC 2016a; Abarca-Gómez et al. 2017 and Doak and Popkin 2017). As a result, in every region of the world, the prevalence of obesity (body mass index >30 kg m^{-2}) and overweight (body mass index range between normality [18.5–24.9] and obesity) is increasing. There are now more obese adults in the world than underweight adults (Ng et al. 2014; NCD-RisC 2016a; Abarca-Gómez et al. 2017 and Doak and Popkin 2017). In 2016, around two billion adults were overweight, including 678 million suffering from obesity (NCD-RisC 2016a; Abarca-Gómez et al. 2017). The prevalence of overweight and obesity has been observed in all age groups.

Around 41 million children under five years and 340 million children and adolescents aged 5–19 years were suffering from overweight or obesity in 2016 (NCD-RisC 2016a; FAO et al. 2017; WHO 2015). In many high-income countries, the rising trends in children and adolescents suffering from overweight or obesity have stagnated at high levels; however, these have accelerated in parts of Asia and have very slightly reduced in European and Central Asian lower and middle-income countries (Abarca-Gómez et al. 2017; Doak and Popkin 2017; Christmann et al. 2009).

There are associations between obesity and non-communicable diseases such as diabetes, dementia, inflammatory diseases (Saltiel and Olefsky 2017), cardiovascular disease (Ortega et al. 2016) and some cancers, for example, of the colon, kidney, and liver (Moley and Colditz 2016). There is a growing recognition of the rapid rise in overweight and obesity on a global basis and its associated health burden created through non-communicable diseases (NCD-RisC 2016a; HLPE 2017).

Analyses reported in FAO et al. (2018) highlight the link between food insecurity, as measured by the FIES scale, and malnourishment (*medium agreement, robust evidence*). This varies by malnourishment measure as well as country (FAO et al. 2018). For example, there is *limited evidence* (*low agreement* but multiple studies) that food insecurity and childhood wasting (i.e., or low weight for height) are closely related, but it is very likely (*high agreement, robust evidence*) that childhood stunting and food insecurity are related (FAO et al. 2018). With respect to adult obesity there is *robust evidence, with medium agreement*, that food insecurity, arising from poverty reducing access to nutritious diets, is related to the prevalence of obesity, especially in high-income countries and adult females. An additional meta-analysis (for studies in Europe and North America) also finds a negative relationship between income and obesity, with some support for an effect of obesity causing low income (as well as vice versa) (Kim and von dem Knesebeck 2018).

As discussed in Section 5.1.1.1, different methods of assessing food insecurity can provide differential pictures. Of particular note is the spatial distribution of food insecurity, especially in higher-income countries. FAO et al. (2018) reports FIES estimates of severe food insecurity in Africa, Asia and Latin America of 29.8%, 6.9% and 9.8% of the population, respectively, but of 1.4% of the population (i.e., about 20 million in total; pro rata <5 million for US, <1 million for UK) in Europe and North America. However, in the USA, USDA estimates 40 million people were exposed to varying degrees of food insecurity, from mild to severe (overall prevalence about 12%) (Coleman-Jensen et al. 2018). In the UK, estimates from 2017 and 2018 indicate about 4 million adults are moderately to severely food insecure (prevalence 8%) (End Hunger UK 2018; Bates et al. 2017). The UK food bank charity, the Trussell Trust, over a year in 2017/18, distributed 1,332,952 three-day emergency food parcels to people referred to the charity as being in food crisis. Furthermore, a 2003 study in the UK (Schenker 2003) estimated that 40% of adults, and 15% of children admitted to hospitals were malnourished, and that 70% of undernourishment in the UK was unreported.

In total, more than half the world's population are underweight or overweight (NCD-RisC 2017a), so their diets do not provide the conditions for 'an active and healthy life'. This will be more compromised under the impacts of climate change by changing the availability, access, utilisation, and stability of diets of sufficient nutritional quality as shown in Table 5.2 and discussed in detail below (Section 5.2).

5.1.3 Climate change, gender and equity

Throughout, the chapter considers many dimensions of gender and equity in regard to climate change and the food system (Box 5.1). Climate change impacts differ among diverse social groups depending on factors such as age, ethnicity, ability/disability, sexual orientation, gender, wealth, and class (*high confidence*) (Vincent and Cull 2014; Kaijser and Kronsell 2014). Poverty, along with socio-economic and political marginalisation, cumulatively put women, children and the elderly in a disadvantaged position in coping with the adverse impacts of the changing climate (UNDP 2013; Skoufias et al. 2011). The contextual vulnerability of women is higher due to their differentiated relative power, roles, and responsibilities at the household and community levels (Bryan and Behrman 2013; Nelson et al. 2002). They often have a higher reliance on subsistence agriculture, which will be severely impacted by climate change (Aipira et al. 2017).

Through impacts on food prices (Section 5.2.3.1) poor people's food security is particularly threatened. Decreased yields can impact nutrient intake of the poor by decreasing supplies of highly nutritious crops and by promoting adaptive behaviours that may substitute crops that are resilient but less nutritious (Thompson et al. 2012; Lobell and Burke 2010). In Guatemala, food prices and poverty have been correlated with lower micronutrient intakes (Iannotti et al. 2012). In the developed world, poverty is more typically associated with calorically-dense but nutrient-poor diets, obesity, overweight, and other related diseases (Darmon and Drewnowski 2015).

Rural areas are especially affected by climate change (Dasgupta et al. 2014), through impacts on agriculture-related livelihoods and rural income (Mendelsohn et al. 2007) and through impacts on employment. Jessoe et al. (2018) using a 28-year panel on individual employment in rural Mexico, found that years with a high occurrence of heat lead to a reduction in local employment by up to 1.4% with a medium emissions scenario, particularly for wage work and non-farm labour, with impacts on food access. Without employment opportunities in areas where extreme poverty is prevalent, people may be forced to migrate, exacerbating potential for ensuing conflicts (FAO 2018a).

Finally, climate change can affect human health in other ways that interact with food utilisation. In many parts of the world where agriculture relies still on manual labour, projections are that heat stress will reduce the hours people can work, and increase their risk (Dunne et al. 2013). For example, Takakura et al. (2017) estimates that under RCP8.5, the global economic loss from people working shorter hours to mitigate heat loss may be 2.4–4% of GDP. Furthermore, as discussed by Watts et al. (2018); people's nutritional status interacts with other stressors and affects their susceptibility to ill health (the 'utilisation pillar' of food security): so food-insecure people are more likely to be adversely affected by extreme heat, for example.

In the case of food price hikes, those more vulnerable are more affected (Uraguchi 2010), especially in urban areas (Ruel et al. 2010), where livelihood impacts are particularly severe for the individuals and groups that have scarce resources or are socially isolated (Revi et al. 2014; Gasper et al. 2011) (*high confidence*). These people often lack power and access to resources, adequate urban services and functioning infrastructure. As climate events become more frequent and intense, this can increase the scale and depth of urban poverty (Rosenzweig et al. 2018b). Urban floods and droughts may result in water contamination increasing the incidence of diarrhoeal illness in poor children (Bartlett 2008). In the near destruction of New Orleans by Hurricane Katrina, about 40,000 jobs were lost (Rosemberg 2010).

Box 5.1 | Gender, food security and climate change

Differentiated impacts, vulnerability, risk perception, behaviours and coping strategies for climate change related to food security derive from cultural (gendered) norms. That is, the behaviours, tasks, and responsibilities a society defines as 'male' or 'female', and the differential gendered access to resources (Paris and Rola-Rubzen 2018; Aberman and Tirado 2014; Lebel et al. 2014; Bee 2016). In many rural areas women often grow most of the crops for domestic consumption and are primarily responsible for storing, processing, and preparing food; handling livestock; gathering food, fodder and fuelwood; managing domestic water supply; and providing most of the labour for post-harvest activities (FAO 2011a). They are mostly impacted through increased hardship, implications for household roles, and subsequent organisational responsibilities (Boetto and McKinnon 2013; Jost et al. 2016). Water scarcity can particularly affect women because they need to spend more time and energy to collect water, where they may be more exposed to physical and sexual violence (Sommer et al. 2015; Aipira et al. 2017). They may be forced to use unsafe water in the household increasing risk of water-borne diseases (Parikh 2009). Climate change also has differentiated gendered impacts on livestock-holders' food security (McKune et al. 2015; Ongoro and Ogara 2012; Fratkin et al. 2004) (Supplementary Material Table SM5.1).

Gender dimensions of the four pillars

Worldwide, women play a key role in food security (World Bank 2015) and the four pillars of food security have strong gender dimensions (Thompson 2018). In terms of **food availability**, women tend to have less access to productive resources, including land, and thus less capacity to produce food (Cross-Chapter Box 11 in Chapter 7).

In terms of **food access**, gendered norms in how food is divided at mealtimes may lead to smaller food portions for women and girls. Women's intra-household inequity limits their ability to purchase food; limitations also include lack of women's mobility impacting trips to the market and lack of decision-making within the household (Ongoro and Ogara 2012; Mason et al. 2017; Riley and Dodson 2014).

In terms of **food utilisation**, men, women, children and the elderly have different nutritional needs (e.g., during pregnancy or breast-feeding).

In terms of **food stability**, women are more likely to be disproportionately affected by price spikes (Vellakkal et al. 2015; Arndt et al. 2016; Hossain and Green 2011; Darnton-Hill and Cogill 2010; Cohen and Garrett 2010; Kumar and Quisumbing 2013) because when food is scarce women reduce food consumption relative to other family members, although these norms vary according to age, ethnicity, culture, region, and social position, as well as by location in rural or urban areas (Arora-Jonsson 2011; Goh 2012; Niehof 2016; Ongoro and Ogara 2012).

Integrating gender into adaptation

Women have their own capabilities to adapt to climate change. In the Pacific Islands, women hold critical knowledge on where or how to find clean water; which crops to grow in a wet or dry season; how to preserve and store food and seeds ahead of approaching storms,

Box 5.1 (continued)

floods or droughts; and how to carry their families through the recovery months. They also play a pivotal role in managing household finances and investing their savings in education, health, livelihoods, and other activities that assist their families to adapt and respond to climate effects (Aipira et al. 2017). Decreasing women's capacity to adapt to the impacts of climate change also decreases that of the household (Bryan and Behrman 2013).

However, gender norms and power inequalities also shape the ability of men, women, boys, girls and the elderly to adapt to climate risks (Rossi and Lambrou 2008). For example, women pastoralists in the Samburu district of Kenya cannot make decisions affecting their lives, limiting their adaptive capacity (Ongoro and Ogara 2012).

Participation in decision-making and politics, division of labour, resource access and control, and knowledge and skills (Nelson and Stathers 2009) are some of the barriers to adaptation. Women's adaptive capacity is also diminished because their work often goes unrecognised (Rao 2005; Nelson and Stathers 2009). Many of women's activities are not defined as 'economically active employment' in national accounts (FAO 2011a). This non-economic status of women's activities implies that they are not included in wider discussions of priorities or interventions for climate change. Their perspectives and needs are not met; and thus, interventions, information, technologies, and tools promoted are potentially not relevant, and even can increase discrimination (Alston 2009; Edvardsson Björnberg and Hansson 2013; Huynh and Resurreccion 2014).

Where gender-sensitive policies to climate change may exist, effective implementation in practice of gender equality and empowerment may not be achieved on the ground due to lack of technical capacity, financial resources and evaluation criteria, as shown in the Pacific Islands (Aipira et al. 2017). Thus, corresponding institutional frameworks that are well-resourced, coordinated, and informed are required, along with adequate technical capacity within government agencies, NGOs and project teams, to strengthen collaboration and promote knowledge sharing (Aipira et al. 2017).

Women's empowerment: Synergies among adaptation, mitigation, and food security

Empowering and valuing women in their societies increases their capacity to improve food security under climate change and make substantial contributions to their own well-being, to that of their families and of their communities (Langer et al. 2015; Ajani et al. 2013 and Alston 2014) (*high confidence*). Women's empowerment includes economic, social and institutional arrangements and may include targeting men in integrated agriculture programmes to change gender norms and improve nutrition (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 scale (Ringler et al. 2014). Empowered women are crucial to creating effective synergies among adaptation, mitigation, and food security.

In Western Kenya, widows in their new role as main livelihood providers invested in sustainable innovations like rainwater harvesting systems and agroforestry (this can serve as both adaptation and mitigation), and worked together in formalised groups of collective action (Gabrielsson and Ramasar 2013) to ensure food and water security. In Nepal, women's empowerment had beneficial outcomes in maternal and children nutrition, reducing the negative effect of low production diversity (Malapit et al. 2015). Integrated nutrition and agricultural programmes have increased women's decision-making power and control over home gardens in Burkina Faso (van den Bold et al. 2015) with positive impacts on food security.

5.1.4 Food systems in AR5, SR15, and the Paris Agreement

Food, and its relationship to the environment and climate change, has grown in prominence since the Rio Declaration in 1992, where food production is Chapter 14 of Agenda 21, to the Paris Agreement of 2015, which includes the need to ensure food security under the threat of climate change on its first page. This growing prominence of food is reflected in recent IPCC reports, including its Fifth Assessment Report (IPCC 2014a) and the Special Report on global warming of 1.5°C (SR15) (IPCC 2018a).

5.1.4.1 Food systems in AR5 and SR15

The IPCC Working Group (WG) II AR5 chapter on Food Security and Food Production Systems broke new ground by expanding its focus beyond the effects of climate change primarily on agricultural production (crops, livestock and aquaculture) to include a food systems approach as well as directing attention to undernourished people (Porter et al. 2014). However, it focused primarily on food production systems due to the prevalence of studies on that topic (Porter et al. 2017). It highlighted that a range of potential adaptation options exist across all food system activities, not just in food production, and that benefits from potential innovations in food processing, packaging, transport, storage, and trade were insufficiently researched at that time.

The IPCC WG III AR5 chapter on Agriculture, Forestry and Other Land Use (AFOLU) (Smith et al. 2014) assessed mitigation potential considering not only the supply, but also the demand side of land uses, by consideration of changes in diets; it also included food loss and waste. AR5 focused on crop and livestock activities within the farm gate and land use and land-use change dynamics associated with agriculture. It did not take a full food system approach to emissions estimates that include processing, transport, storage, and retail.

The IPCC WG II AR5 Rural Areas chapter (Revi et al. 2014) found that farm households in developing countries are vulnerable to climate change due to socio-economic characteristics and non-climate stressors, as well as climate risks (Dasgupta et al. 2014). They also found that a wide range of on-farm and off-farm climate change adaptation measures are already being implemented and that the local social and cultural context played a prominent role in the success or failure of different adaptation strategies for food security, such as trade, irrigation or diversification. The IPCC WG II AR5 Urban Areas chapter found that food security for people living in cities was severely affected by climate change through reduced supplies, including urban-produced food, and impacts on infrastructure, as well as a lack of access to food. Poor urban dwellers are more vulnerable to rapid changes of food prices due to climate change.

Many climate change response options in IPCC WG II and WG III AR5 (IPCC 2014b) address incremental adaptation or mitigation responses separately rather than being inclusive of more systemic or transformational changes in multiple food systems that are large-scale, in depth, and rapid, requiring social, technological, organisational and system responses (Rosenzweig and Solecki 2018; Mapfumo et al. 2017; Termeer et al. 2017). In many cases, transformational change will require integration of resilience and mitigation across all parts of the food system including production, supply chains, social aspects, and dietary choices. Further, these transformational changes in the food system need to encompass linkages to ameliorative responses to land degradation (Chapter 4), desertification (Chapter 3), and declines in quality and quantity of water resources throughout the food-energy-water nexus (Chapter 2 and Section 5.7).

The IPCC Special Report on global warming of 1.5°C found that climate-related risks to food security are projected to increase with global warming of 1.5°C and increase further with 2°C (IPCC 2018a).

5.1.4.2 Food systems and the Paris Agreement

To reach the temperature goal put forward in the Paris Agreement of limiting warming to well below 2°C, and pursuing efforts to limit warming to 1.5°C, representatives from 196 countries signed the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement (UNFCCC 2015) in December 2015. The Agreement put forward a temperature target of limiting warming to well below 2°C, and pursuing efforts to limit warming to 1.5°C. Under the Paris Agreement, Parties are expected to put forward their best efforts through nationally determined contributions (NDCs) and to strengthen these efforts in the years ahead. Article 2 of the Agreement makes clear the agreement is within 'the context of sustainable development' and states actions should be 'in a manner that does not threaten food production' to ensure food security.

Many countries have included food systems in their mitigation and adaptation plans as found in their NDCs for the Paris Agreement (Rosenzweig et al. 2018a). Richards et al. (2015) analysed 160 Party submissions and found that 103 include agricultural mitigation; of the 113 Parties that include adaptation in their NDCs, almost all (102) include agriculture among their adaptation priorities. There is much attention to conventional agricultural practices that can be climate-smart and sustainable (e.g., crop and livestock management), but less to the enabling services that can facilitate uptake (e.g., climate information services, insurance, credit). Considerable finance is needed for agricultural adaptation and mitigation by the least developed countries – in the order of 3 billion USD annually for adaptation and 2 billion USD annually for mitigation, which may be an underestimate due to a small sample size (Richards et al. 2015). On the mitigation side, none of the largest agricultural emitters included sector-specific contributions from the agriculture sector in their NDCs, but most included agriculture in their economy-wide targets (Richards et al. 2018).

Carbon dioxide removal (CDR). A key aspect regarding the implementation of measures to achieve the Paris Agreement goals involves measures related to carbon dioxide removal (CDR) through bioenergy (Sections 5.5 and 5.6). To reach the temperature target of limiting warming to well below 2°C, and pursuing efforts to limit warming to 1.5°C, large investments and abrupt changes in land use will be required to advance bioenergy with carbon capture and sequestration (BECCS), afforestation and reforestation (AR), and biochar technologies. Existing scenarios estimate the global area required for energy crops to help limit warming to 1.5°C in the range of 109–990 Mha, most commonly around 380–700 Mha.

Most scenarios assume very rapid deployment between 2030 and 2050, reaching rates of expansion in land use in 1.5°C scenarios exceeding 20 Mha yr^{-1}, which are unprecedented for crops and forestry reported in the FAO database from 1961. Achieving the 1.5°C target would thus result in major competing demands for land between climate change mitigation and food production, with cascading impacts on food security.

This chapter assesses how the potential conflict for land could be alleviated by sustainable intensification to produce food with a lower land footprint (Cross-Chapter Box 6 in Section 5.6). To accomplish this, farmers would need to produce the same amount of food with lower land requirement, which depends on technology, skills, finance, and markets. Achieving this would also rely on demand-side changes including dietary choices that enable reduction of the land footprint for food production while still meeting dietary needs. Transitions required for such transformative changes in food systems are addressed in Section 5.7.

5.1.4.3 Charting the future of food security

This chapter utilises the common framework of the Representative Concentration Pathways (RCPs) and the Shared Socio-economic Pathways (SSPs) (Popp et al. 2017; Riahi et al. 2017 and Doelman et al. 2018) to assess the impacts of future GHG emissions, mitigation measures, and adaptation on food security (Cross-Chapter Box 1 in Chapter 1, Sections 5.2 and 5.6).

New work utilising these scenario approaches has shown that the food system externalises costs onto human health and the environment (Springmann et al. 2018a; Swinburn et al. 2019; Willett et al. 2019), leading to calls for transforming the food system to deliver better human and sustainability outcomes (Willett et al. 2019; IAP 2018; Development Initiatives 2018; Lozano et al. 2018). Such a transformation could be an important lever to address the complex interactions between climate change and food security. Through acting on mitigation and adaptation in regard to both food demand and food supply we assess the potential for improvements to both human health and the Sustainable Development Goals (Section 5.6).

This chapter builds on the food system and scenario approaches followed by AR5 and its focus on climate change and food security, but new work since AR5 has extended beyond production to how climate change interacts with the whole food system. The analysis of climate change and food insecurity has expanded beyond undernutrition to include the over-consumption of unhealthy mass-produced food high in sugar and fat, which also threatens health in different but highly damaging ways, as well as the role of dietary choices and consumption in GHG emissions. It focuses on land-based food systems, though highlighting in places the contributions of freshwater and marine production.

The chapter assesses new work on the observed and projected effects of CO_2 concentrations on the nutritional quality of crops (Section 5.2.4.2) emphasising the role of extreme climate events (Section 5.2.5.1), social aspects including gender and equity (Box 5.1, and Cross-Chapter Box 11 in Chapter 7), and dietary choices (Section 5.4.6, 5.5.2). Other topics with considerable new literature include impacts on smallholder farming systems (Section 5.2.2.6), food loss and waste (Section 5.5.2.5), and urban and peri-urban agriculture (Section 5.6.5). The chapter explores the potential competing demands for land that mitigation measures to achieve temperature targets may engender, with cascading impacts on food production, food security, and farming systems (Section 5.6), and the enabling conditions for achieving mitigation and adaptation in equitable and sustainable ways (Section 5.7). Section 5.8 presents challenges to future food security, including food price spikes, migration, and conflict.

5.2 Impacts of climate change on food systems

There are many routes by which climate change can impact food security and thus human health (Watts et al. 2018; Fanzo et al. 2017). One major route is via climate change affecting the amount of food, both from direct impacts on yields (Section 5.2.2.1) and indirect effects through climate change's impacts on water availability and quality, pests and diseases (Section 5.2.2.3), and pollination services (Section 5.2.2.4). Another route is via changing CO_2 in the atmosphere, affecting biomass and nutritional quality (Section 5.2.4.2). Food safety risks during transport and storage can also be exacerbated by changing climate (Section 5.2.4.1).

Further, the direct impacts of changing weather can affect human health through the agricultural workforce's exposure to extreme temperatures (Section 5.2.5.1). Through changing metabolic demands and physiological stress for people exposed to extreme temperatures, there is also the potential for interactions with food availability; people may require more food to cope, whilst at the same time being impaired from producing it (Watts et al. 2018). All these factors have the potential to alter both physical health as well as cultural health, through changing the amount, safety and quality of food available for individuals within their cultural context.

This section assesses recent literature on climate change impacts on the four pillars of food security: availability (Section 5.2.2), access (Section 5.2.3), utilisation (Section 5.2.4), and stability (Section 5.2.5). It considers impacts on the food system from climate changes that are already taking place and how impacts are projected to occur in the future. See Supplementary Material Section SM5.2 for discussion of detection and attribution and improvement in projection methods.

5.2.1 Climate drivers important to food security

Climate drivers relevant to food security and food systems include temperature-related, precipitation-related, and integrated metrics that combine these and other variables. These are projected to affect many aspects of the food security pillars (FAO 2018b) (see Supplementary Material Table SM5.2, and Chapter 6 for assessment of observed and projected climate impacts). Climate drivers relevant to food production and availability may be categorised as modal climate changes (e.g., shifts in climate envelopes causing shifts in cropping varieties planted), seasonal changes (e.g., warming trends extending growing seasons), extreme events (e.g., high temperatures affecting critical growth periods, flooding/droughts), and atmospheric conditions for example, CO_2 concentrations, short-lived climate pollutants (SLCPs), and dust. Water resources for food production will be affected through changing rates of precipitation and evaporation, ground water levels, and dissolved oxygen content (Cruz-Blanco et al. 2015; Sepulcre-Canto et al. 2014; Huntington et al. 2017; Schmidtko et al. 2017). Potential changes in major modes of climate variability can also have widespread impacts such as those that occurred during late 2015 to early 2016 when a strong El Niño contributed to regional shifts in precipitation in the Sahel region. Significant drought across Ethiopia resulted in widespread crop failure and more than 10 million people in Ethiopia requiring food aid (U.S. Department of State 2016; Huntington et al. 2017) (Figure 5.3).

Other variables that affect agricultural production, processing, and/or transport are solar radiation, wind, humidity, and (in coastal areas) salinisation and storm surge (Mutahara et al. 2016; Myers et al. 2017).

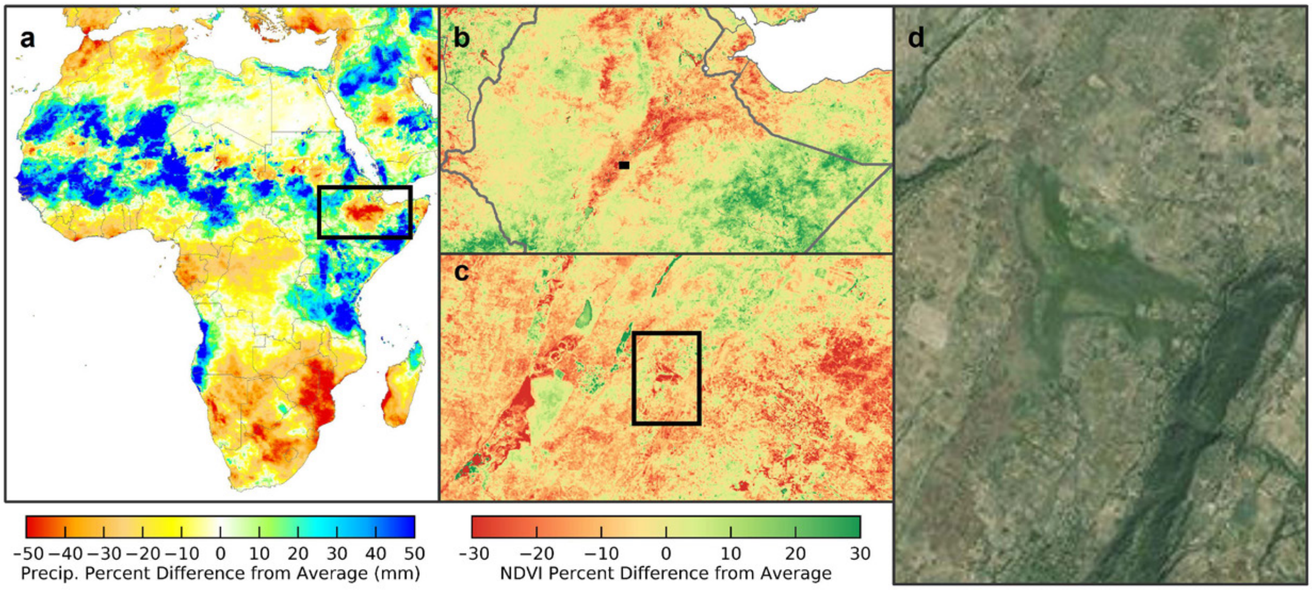

Figure 5.3 | Precipitation anomaly and vegetation response in eastern Africa. (a) Sep 2015–Feb 2016 Climate Hazards Group Infrared Precipitation with Station (CHIRPS) precipitation anomaly over Africa relative to the 1981–2010 average shows that large areas of Ethiopia received less than half of normal precipitation. Consequently, widespread impacts to agricultural productivity, especially within pastoral regions, were present across Ethiopia as evidenced by **(d)** reduced greenness in remote sensing images. **(b)** MODIS NDVI anomalies for Sep 2015–Feb 2016 relative to 2000–2015 average are shown for the inset box in (a). **(c)** Landsat NDVI anomalies for Sep 2015–Feb 2016 relative to 2000–2015 average are shown for the inset box in (b) (Huntington et al. 2017).

Extreme climate events resulting in inland and coastal flooding, can affect the ability of people to obtain and prepare food (Rao et al. 2016; FAO et al. 2018). For direct effects of atmospheric CO_2 concentrations on crop nutrient status see Section 5.2.4.2.

5.2.1.1 Short-lived climate pollutants

The important role of short-lived climate pollutants such as ozone and black carbon is increasingly emphasised since they affect agricultural production through direct effects on crops and indirect effects on climate (Emberson et al. 2018; Lal et al. 2017; Burney and Ramanathan 2014; Ghude et al. 2014) (Chapters 2 and 4). Ozone causes damage to plants through damages to cellular metabolism that influence leaf-level physiology to whole-canopy and root-system processes and feedbacks; these impacts affect leaf-level photosynthesis senescence and carbon assimilation, as well as whole-canopy water and nutrient acquisition and ultimately crop growth and yield (Emberson et al. 2018).

Using atmospheric chemistry and a global integrated assessment model, Chuwah et al. (2015) found that without a large decrease in air pollutant emissions, high ozone concentration could lead to an increase in crop damage of up to 20% in agricultural regions in 2050 compared to projections in which changes in ozone are not accounted for. Higher temperatures are associated with higher ozone concentrations; C3 crops are sensitive to ozone (e.g., soybeans, wheat, rice, oats, green beans, peppers, and some types of cottons) and C4 crops are moderately sensitive (Backlund et al. 2008).

Methane increases surface ozone which augments warming-induced losses and some quantitative analyses now include climate, long-lived (CO_2) and multiple short-lived pollutants (CH_4, O_3) simultaneously (Shindell et al. 2017; Shindell 2016). Reduction of tropospheric ozone and black carbon can avoid premature deaths from outdoor air pollution and increases annual crop yields (Shindell et al. 2012). These actions plus methane reduction can influence climate on shorter time scales than those of carbon dioxide reduction measures. Implementing them substantially reduces the risks of crossing the 2°C threshold and contributes to achievement of the SDGs (Haines et al. 2017; Shindell et al. 2017).

5.2.2 Climate change impacts on food availability

Climate change impacts food availability through its effect on the production of food and its storage, processing, distribution, and exchange.

5.2.2.1 Impacts on crop production

Observed impacts. Since AR5, there have been further studies that document impacts of climate change on crop production and related variables (Supplementary Material Table SM5.3). There have also been a few studies that demonstrate a strengthening relationship between observed climate variables and crop yields that indicate future expected warming will have severe impacts on crop production (Mavromatis 2015; Innes et al. 2015). At the global scale, Iizumi et al. (2018) used a counterfactual analysis and found that climate change between 1981 and 2010 has decreased global mean yields of maize, wheat, and soybeans by 4.1, 1.8 and 4.5%, respectively, relative to preindustrial climate, even when CO_2 fertilisation and agronomic adjustments are considered. Uncertainties (90% probability interval) in the yield impacts are –8.5 to +0.5% for maize, –7.5 to +4.3% for wheat, and –8.4 to –0.5% for soybeans. For rice, no significant impacts were detected. This study suggests that climate change has modulated recent yields on the global scale and led to production losses, and that adaptations to date have not been sufficient to offset the negative impacts of climate change, particularly at lower latitudes.

Dryland settlements are perceived as vulnerable to climate change with regard to food security, particularly in developing countries; such areas are known to have low capacities to cope effectively with decreasing crop yields (Shah et al. 2008; Nellemann et al. 2009). This is of concern because drylands constitute over 40% of the earth's land area, and are home to 2.5 billion people (FAO et al. 2011).

Australia

In Australia, declines in rainfall and rising daily maximum temperatures based on simulations of 50 sites caused water-limited yield potential to decline by 27% from 1990 to 2015, even though elevated atmospheric CO_2 concentrations had a positive effect (Hochman et al. 2017). In New South Wales, high-temperature episodes during the reproduction stage of crop growth were found to have negative effects on wheat yields, with combinations of low rainfall and high temperatures being the most detrimental (Innes et al. 2015).

Asia

There are numerous studies demonstrating that climate change is affecting agriculture and food security in Asia. Several studies with remote sensing and statistical data have examined rice areas in north-eastern China, the northernmost region of rice cultivation, and found expansion over various time periods beginning in the 1980s, with most of the increase occurring after 2000 (Liu et al. 2014; Wang et al. 2014; Zhang et al. 2017). Rice yield increases have also been found over a similar period (Wang et al. 2014). Multiple factors, such as structural adjustment, scientific and technological progress, and government policies, along with regional warming (1.43°C in the past century) (Fenghua et al. 2006) have been put forward as contributing to the observed expanded rice areas and yield in the region. Shi et al. (2013) indicate that there is a partial match between climate change patterns and shifts in extent and location of the rice-cropping area (2000–2010).

There have also been documented changes in winter wheat phenology in Northwest China (He 2015). Consistent with this finding, dates of sowing and emergence of spring and winter wheat were delayed, dates of anthesis and maturity was advanced, and length of reproductive growth period was prolonged from 1981–2011 in a study looking at these crops across China (Liu et al. 2018b). Another study looking in Northwest China demonstrated that there have been changes in the phenology and productivity of spring cotton (Huang and Ji 2015). A counterfactual study looking at wheat growth and yield in different climate zones of China from 1981–2009 found that impacts were positive in northern China and negative in southern China (Tao et al. 2014). Temperature increased across the zones while precipitation changes were not consistent (Tao et al. 2014).

Similar crop yield studies focusing on India have found that warming has reduced wheat yields by 5.2% from 1981 to 2009, despite adaptation (Gupta et al. 2017), and that maximum daytime temperatures have risen along with some night-time temperatures (Jha and Tripathi 2017).

Agriculture in Pakistan has also been affected by climate change. From 1980 to 2014, spring maize growing periods have shifted an average of 4.6 days per decade earlier, while sowing of autumn maize has been delayed 3.0 days per decade (Abbas et al. 2017). A similar study with sunflower showed that increases in mean temperature from 1980 to 2016 were highly correlated with shifts in sowing, emergence, anthesis, and maturity for fall and spring crops (Tariq et al. 2018).

Mountain people in the Hindu-Kush Himalayan region encompassing parts of Pakistan, India, Nepal, and China, are particularly vulnerable to food insecurity related to climate change because of poor infrastructure, limited access to global markets, physical isolation, low productivity, and hazard exposure, including Glacial Lake Outburst Floods (GLOFs) (Rasul et al. 2019; Rasul 2010; Tiwari and Joshi 2012; Huddleston et al. 2003; Ward et al. 2013; FAO 2008; Nautiyal et al. 2007; Din et al. 2014). Surveys have been conducted to determine how climate-related changes have affected food security (Hussain et al. 2016; Shrestha and Nepal 2016) with results showing that the region is experiencing an increase in extremes, with farmers facing more frequent floods as well as prolonged droughts with ensuing negative impacts on agricultural yields and increases in food insecurity (Hussain et al. 2016; Manzoor et al. 2013).

South America

In another mountainous region, the Andes, inhabitants are also beginning to experience changes in the timing, severity, and patterns of the annual weather cycle. Data collected through participatory workshops, semi-structured interviews with agronomists, and qualitative fieldwork from 2012 to 2014 suggest that in Colomi, Bolivia, climate change is affecting crop yields and causing farmers to alter the timing of planting, their soil management strategies, and the use and spatial distribution of crop varieties (Saxena et al. 2016). In Argentina, there has also been an increase in yield variability of maize and soybeans (Iizumi and Ramankutty 2016). These changes have had important implications for the agriculture, human health, and biodiversity of the region (Saxena et al. 2016).

Africa

In recent years, yields of staple crops such as maize, wheat, sorghum, and fruit crops, such as mangoes, have decreased across Africa, widening food insecurity gaps (Ketiem et al. 2017). In Nigeria, there have been reports of climate change having impacts on the livelihoods of arable crop farmers (Abiona et al. 2016; Ifeanyi-obi et al. 2016; Onyeneke 2018). The Sahel region of Cameroon has experienced an increasing level of malnutrition. This is partly due to the impact of climate change since harsh climatic conditions leading to extreme drought have a negative influence on agriculture (Chabejong 2016).

Utilising farmer interviews in Abia State, Nigeria, researchers found that virtually all responders agreed that the climate was changing in their area (Ifeanyi-obi et al. 2016). With regard to management responses, a survey of farmers from Anambra State, Nigeria, showed that farmers are adapting to climate change by utilising such techniques as mixed cropping systems, crop rotation, and fertiliser application (Onyeneke et al. 2018). In Ebonyi State, Nigeria, Eze (2017) interviewed 160 women cassava farmers and found the major climate change risks in production to be severity of high temperature stress, variability in relative humidity, and flood frequency.

Europe

The impacts of climate change are varied across the continent. Moore and Lobell (2015) showed via counterfactual analysis that climate trends are affecting European crop yields, with long-term temperature and precipitation trends since 1989 reducing continent-wide wheat and barley yields by 2.5% and 3.8%, respectively, and having slightly increased maize and sugar beet yields. Though these aggregate affects appear small, the impacts are not evenly distributed. In cooler regions such as the United Kingdom and Ireland, the effect of increased warming has been ameliorated by an increase in rainfall. Warmer regions, such as Southern Europe, have suffered more from the warming; in Italy this effect has been amplified by a drying trend, leading to yield declines of 5% or greater.

Another study examining the impacts of recent climate trends on cereals in Greece showed that crops are clearly responding to changes in climate – and demonstrated (via statistical analysis) that significant impacts on wheat and barley production are expected at the end of the 21st century (Mavromatis 2015). In the Czech Republic, a study documented positive long-term impacts of recent warming on yields of fruiting vegetables (cucumbers and tomatoes) from 4.9 to 12% per 1°C increase in local temperature, but decreases in yield stability of traditionally grown root vegetables in the warmest areas of the country (Potopová et al. 2017). A study in Hungary also indicated the increasingly negative impacts of temperature on crops and indicated that a warming climate is at least partially responsible for the stagnation in crop yields since the mid-1980s in Eastern Europe (Pinke and Lövei 2017).

In summary, climate change is already affecting food security (*high confidence*). Recent studies in both large-scale and smallholder farming systems document declines in crop productivity related to rising temperatures and changes in precipitation. Evidence for climate change impacts (e.g., declines and stagnation in yields, changes in sowing and harvest dates, increased infestation of pests and diseases, and declining viability of some crop varieties) is emerging from detection and attribution studies and ILK in Australia, Europe, Asia, Africa, North America, and South America (*medium evidence, robust agreement*).

Projected impacts

Climate change effects have been studied on a global scale following a variety of methodologies that have recently been compared (Lobell and Asseng 2017; Zhao et al. 2017a and Liu et al. 2016). Approaches to study global and local changes include global gridded crop model simulations (e.g., Deryng et al. 2014), point-based crop model simulations (e.g., Asseng et al. 2015), analysis of point-based observations in the field (e.g., Zhao et al. 2016), and temperature-yield regression models (e.g., Auffhammer and Schlenker 2014). For an evaluation of model skills see example used in AgMIP (Müller et al. 2017b).

Results from Zhao et al. (2017a) across different methods consistently showed negative temperature impacts on crop yield at the global scale, generally underpinned by similar impacts at country and site scales. A limitation of Zhao et al. (2017a) is that it is based on the assumption that yield responses to temperature increase are linear, while yield response differs depending on growing season temperature levels. Iizumi et al. (2017) showed that the projected global mean yields of maize and soybean at the end of this century do decrease monotonically with warming, whereas those of rice and wheat increase with warming but level off at about 3°C (2091–2100 relative to 1850–1900).

Empirical statistical models have been applied widely to different cropping systems, at multiple scales. Analyses using statistical models for maize and wheat tested with global climate model scenarios found that the RCP4.5 scenario reduced the size of average yield impacts,

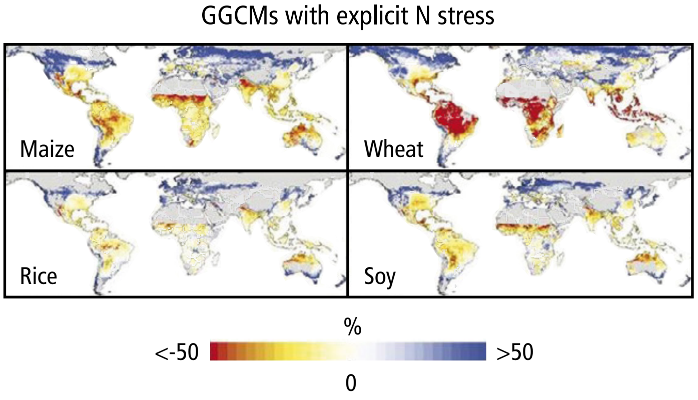

Figure 5.4 | AgMIP median yield changes (%) for RCP8.5 (2070–2099 in comparison to 1980–2010 baseline) with CO_2 effects and explicit nitrogen stress over five GCMs x four Global Gridded Crop Models (GGCMs) for rainfed maize, wheat, rice, and soy (20 ensemble members from EPIC, GEPIC, pDSSAT, and PEGASUS; except for rice which has 15). Grey areas indicate historical areas with little to no yield capacity. All models use a 0.5°C grid, but there are differences in grid cells simulated to represent agricultural land. While some models simulated all land areas, others simulated only potential suitable cropland area according to evolving climatic conditions. Others utilised historical harvested areas in 2000 according to various data sources (Rosenzweig et al. 2014).

risk of major slowdowns, and exposure to critical heat extremes compared to RCP8.5 in the latter decades of the 21st century (Tebaldi and Lobell 2018). Impacts on crops grown in the tropics are projected to be more negative than in mid – to high-latitudes as stated in AR5 and confirmed by recent studies (e.g., Levis et al. 2018). These projected negative effects in the tropics are especially pronounced under conditions of explicit nitrogen stress (Rosenzweig et al. 2014) (Figure 5.4).

Reyer et al. (2017b) examined biophysical impacts in five world regions under different warming scenarios: 1°C, 1.5°C, 2°C, and 4°C warming. For the Middle East and northern African region a significant correlation between crop yield decrease and temperature increase was found, regardless of whether the effects of CO_2 fertilisation or adaptation measures are taken into account (Waha et al. 2017). For Latin America and the Caribbean the relationship between temperature and crop yield changes was only significant when the effect of CO_2 fertilisation is considered (Reyer et al. 2017a).

A review of recent scientific literature found that projected yield loss for West Africa depends on the degree of wetter or drier conditions and elevated CO_2 concentrations (Sultan and Gaetani 2016). Faye et al. (2018b) in a crop modelling study with RCPs 4.5 and 8.5 found that climate change could have limited effects on peanut yield in Senegal due to the effect of elevated CO_2 concentrations.

Crop productivity changes for 1.5°C and 2.0°C. The IPCC Special Report on global warming of 1.5°C found that climate-related risks to food security are projected to increase with global warming of 1.5°C and increase further with 2°C (IPCC 2018b). These findings are based among others on Schleussner et al. (2018); Rosenzweig et al. (2018a); Betts et al. (2018), Parkes et al. (2018) and Faye et al. (2018a). The importance of assumptions about CO_2 fertilisation was found to be significant by Ren et al. (2018) and Tebaldi and Lobell (2018).

AgMIP coordinated global and regional assessment (CGRA) results confirm that at the global scale, positive and negative changes are mixed in simulated wheat and maize yields, with declines in some breadbasket regions, at both 1.5°C and 2.0°C (Rosenzweig et al. 2018a). In conjunction with price changes from the global economics models, productivity declines in the Punjab, Pakistan resulted in an increase in vulnerable households and poverty rate (Rosenzweig et al. 2018a).

Crop suitability. Another method of assessing the effects of climate change on crop yields that combined observations of current maximum-attainable yield with climate analogues also found strong reductions in attainable yields across a large fraction of current cropland by 2050 (Pugh et al. 2016). However, the study found the projected total land area in 2050, including regions not currently used for crops, climatically suitable for a high attainable yield similar to today. This indicates that large shifts in land-use patterns and crop choice will likely be necessary to sustain production growth and keep pace with current trajectories of demand.

Fruits and vegetables. Understanding the full range of climate impacts on fruits and vegetables is important for projecting future food security, especially related to dietary diversity and healthy diets. However, studies for vegetables are very limited (Bisbis et al. 2018). Of the 174 studies considered in a recent review, only 14 described results of field or greenhouse experiments studying impacts of increased temperatures on yields of different root and leafy vegetables, tomatoes and legumes (Scheelbeek et al. 2018). Bisbis et al. (2018) found similar effects for vegetables as have been found for grain crops. That is, the effect of increased CO_2 on vegetables is mostly beneficial for production, but may alter internal product quality, or result in photosynthetic down-regulation. Heat stress reduces fruit set of fruiting vegetables, and speeds up development of annual vegetables, shortening their time for photoassimilation. Yield losses and impaired product quality result, thereby increasing food loss and waste. On the other hand, a longer growing season due to warmer temperatures enables a greater number of plantings and can contribute to greater annual yields. However, some vegetables, such as cauliflower and asparagus, need a period of cold accumulation to produce a harvest and warmer winters may not provide those requirements.

For vegetables growing in higher baseline temperatures (>20°C), mean yield declines caused by 4°C warming were 31.5%; for vegetables growing in cooler environments (≤20°C), yield declines caused by 4°C were much less, on the order of about 5% (Scheelbeek et al. 2018). Rippke et al. (2016) found that 30–60% of the common bean growing area and 20–40% of the banana growing areas in Africa will lose viability in 2078–2098 with a global temperature increase of 2.6°C and 4°C respectively. Tripathi et al. (2016) found fruits and vegetable production to be highly vulnerable to climate change at their reproductive stages and also due to potential for greater disease pressure.

In summary, studies assessed find that climate change will increasingly be detrimental to crop productivity as levels of warming progress (*high confidence*). Impacts will vary depending on CO_2 concentrations, fertility levels, and region. Productivity of major commodity crops as well as crops such as millet and sorghum yields will be affected. Studies on fruits and vegetables find similar effects to those projected for grain crops in regard to temperature and CO_2 effects. Total land area climatically suitable for high attainable yield, including regions not currently used for crops, will be similar in 2050 to today.

5.2.2.2 Impacts on livestock production systems

Livestock systems are impacted by climate change mainly through increasing temperatures and precipitation variation, as well as atmospheric carbon dioxide (CO_2) concentration and a combination of these factors. Temperature affects most of the critical factors of livestock production, such as water availability, animal production and reproduction, and animal health (mostly through heat stress) (Figure 5.5). Livestock diseases are mostly affected by increases in temperature and precipitation variation (Rojas-Downing et al. 2017). Impacts of climate change on livestock productivity, particularly of mixed and extensive systems, are strongly linked to impacts on rangelands and pastures, which include the effects of increasing CO_2 on their biomass and nutritional quality. This is critical considering the very large areas concerned and the number of vulnerable people affected (Steinfeld 2010; Morton 2007). Pasture quality and quantity are mainly affected through increases in temperature and CO_2, and precipitation variation.

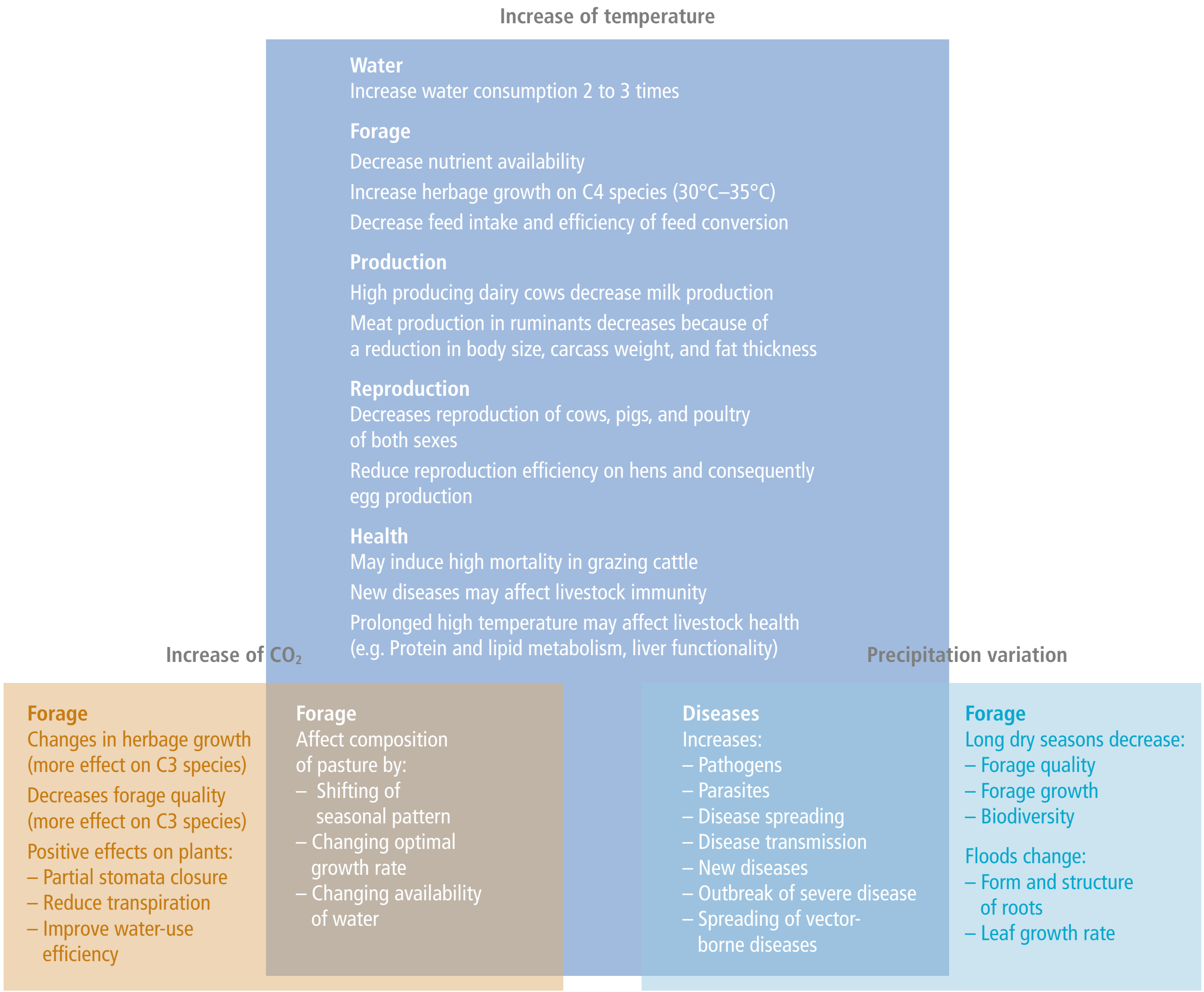

Figure 5.5 | Impacts of climate change on livestock (based on Rojas-Downing et al. 2017).

Among livestock systems, pastoral systems are particularly vulnerable to climate change (Dasgupta et al. 2014) (see Section 5.2.2.6 for impacts on smallholder systems that combine livestock and crops). Industrial systems will suffer most from indirect impacts leading to rises in the costs of water, feeding, housing, transport and the destruction of infrastructure due to extreme events, as well as an increasing volatility of the price of feedstuff which increases the level of uncertainty in production (Rivera-Ferre et al. 2016b; Lopez-i-Gelats 2014). Mixed systems and industrial or landless livestock systems could encounter several risk factors mainly due to the variability of grain availability and cost, and low adaptability of animal genotypes (Nardone et al. 2010).

Considering the diverse typologies of animal production, from grazing to industrial, Rivera-Ferre et al. (2016b) distinguished impacts of climate change on livestock between those related to extreme events and those related to more gradual changes in the average of climate-related variables. Considering vulnerabilities, they grouped the impacts as those impacting the animal directly, such as heat and cold stress, water stress, physical damage during extremes; and others impacting their environment, such as modification in the geographical distribution of vector-borne diseases, location, quality and quantity of feed and water and destruction of livestock farming infrastructures.

With severe negative impacts due to drought and high frequency of extreme events, the average gain of productivity might be cancelled by the volatility induced by increasing variability in the weather. For instance, semi-arid and arid pasture will likely have reduced livestock productivity, while nutritional quality will be affected by CO_2 fertilisation (Schmidhuber and Tubiello 2007).

Observed impacts. Pastoralism is practiced in more than 75% of countries by between 200 and 500 million people, including nomadic communities, transhumant herders, and agropastoralists (McGahey et al. 2014). Observed impacts in pastoral systems reported in the literature include decreasing rangelands, decreasing mobility, decreasing livestock numbers, poor animal health, overgrazing, land degradation, decreasing productivity, decreasing access to water and feed, and increasing conflicts for the access to pasture land (*high confidence*) (López-i-Gelats et al. 2016; Batima et al. 2008; Njiru 2012; Fjelde and von Uexkull 2012; Raleigh and Kniveton 2012; Egeru 2016).

Pastoral systems in different regions have been affected differently. For instance, in China changes in precipitation were a more important factor in nomadic migration than temperature (Pei and Zhang 2014). There is some evidence that recent years have already seen an increase in grassland fires in parts of China and tropical Asia (IPCC 2012). In Mongolia, grassland productivity has declined by 20–30% over the latter half of the 20th century, and ewe average weight reduced by 4 kg on an annual basis, or about 8% since 1980 (Batima et al. 2008). Substantial decline in cattle herd sizes can be due to increased mortality and forced off-take (Megersa et al. 2014). Important, but less studied, is the impact of the interaction of grazing patterns with climate change on grassland composition. Spence et al. (2014) showed that climate change effects on Mongolia mountain steppe could be contingent on land use.

Conflicts due to resource scarcity, as well as other socio-political factors (Benjaminsen et al. 2012) aggravated by climate change, has differentiated impact on women. In Turkana, female-headed households have lower access to decision-making on resource use and allocation, investment and planning (Omolo 2011), increasing their vulnerability (Cross-Chapter Box 11 in Chapter 7, Section 5.1.3).

Non-climate drivers add vulnerability of pastoral systems to climate change (McKune and Silva 2013). For instance, during environmental disasters, livestock holders have been shown to be more vulnerable to food insecurity than their crop-producing counterparts because of limited economic access to food and unfavourable market exchange rates (Nori et al. 2005). Sami reindeer herders in Finland showed reduced freedom of action in response to climate change due to loss of habitat, increased predation, and presence of economic and legal constraints (Tyler et al. 2007; Pape and Löffler 2012). In Tibet, emergency aid has provided shelters and privatised communally owned rangeland, which have increased the vulnerability of pastoralists to climate change (Yeh et al. 2014; Næss 2013).

Projected impacts. The impacts of climate change on global rangelands and livestock have received comparatively less attention than the impacts on crop production. Projected impacts on grazing systems include changes in herbage growth (due to changes in atmospheric CO_2 concentrations and rainfall and temperature regimes) and changes in the composition of pastures and in herbage quality, as well as direct impacts on livestock (Herrero et al. 2016b). Droughts and high temperatures in grasslands can also be a predisposing factor for fire occurrence (IPCC 2012).

Net primary productivity, soil organic carbon, and length of growing period. There are large uncertainties related to grasslands and grazing lands (Erb et al. 2016), especially in regard to net primary productivity (NPP) (Fetzel et al. 2017; Chen et al. 2018). Boone et al. (2017) estimated that the mean global annual net primary production (NPP) in rangelands may decline by 10 gC m^{-2} yr^{-1} in 2050 under RCP8.5, but herbaceous NPP is likely to increase slightly (i.e., average of 3 gC m^{-2} yr^{-1}) (Figure 5.6). Results of a similar magnitude were obtained by Havlík et al. (2015), using EPIC and LPJmL on a global basis. According to Rojas-Downing et al. (2017), an increase of 2°C is estimated to negatively impact pasture and livestock production in arid and semi-arid regions and positively impact humid temperate regions.

Boone et al. (2017) identified significant regional heterogeneity in responses, with large increases in annual productivity projected in northern regions (e.g., a 21% increase in productivity in the USA and Canada) and large declines in western Africa (–46% in Sub-Saharan western Africa) and Australia (–17%). Regarding the length of growing period (LGP, average number of growing days per year) Herrero et al. (2016b) projected reductions in lower latitudes due to changes in rainfall patterns and increases in temperatures, which indicate increasing limitations of water. They identified 35°C as a critical threshold for rangeland vegetation and heat tolerance in some livestock species.

Rangeland composition. According to Boone et al. (2017), the composition of rangelands is projected to change as well (Chapter 3). Bare ground cover is projected to increase, averaging 2.4% across rangelands, with increases projected for the eastern Great Plains, eastern Australia, parts of southern Africa, and the southern Tibetan Plateau. Herbaceous cover declines are projected in the Tibetan Plateau, the eastern Great Plains, and scattered parts of the Southern Hemisphere. Shrub cover is projected to decline in eastern Australia, parts of southern Africa, the Middle East, the Tibetan Plateau, and the eastern Great Plains. Shrub cover could also increase in much of the Arctic and some parts of Africa. In mesic and semi-arid savannas south of the Sahara, both shrub and tree cover are projected to increase, albeit at lower productivity and standing biomass. Rangelands in western and south-western parts of the Isfahan province in Iran were found to be more vulnerable to future drying–warming conditions (Saki et al. 2018; Jaberalansar et al. 2017).

Soil degradation and expanding woody cover suggest that climate-vegetation-soil feedbacks catalysing shifts toward less productive, possibly stable states (Ravi et al. 2010) may threaten mesic and semi-arid savannas south of the Sahara (Chapters 3 and 4). This will also change their suitability for grazing different animal species; switches from cattle, which mainly consume herbaceous plants, to goats or camels are likely to occur as increases in shrubland occur.

Direct and indirect effects on livestock. Direct impacts of climate change in mixed and extensive production systems are linked to increased water and temperature stress on the animals potentially leading to animal morbidity, mortality and distress sales. Most livestock species have comfort zones between 10ºC–30ºC, and at temperatures above this animals reduce their feed intake 3–5% per additional degree of temperature (NRC 1981). In addition to reducing animal production, higher temperatures negatively affect fertility (HLPE 2012).

Indirect impacts to mixed and extensive systems are mostly related to the impacts on the feed base, whether pastures or crops, leading to increased variability and sometimes reductions in availability and quality of the feed for the animals (Rivera-Ferre et al. 2016b). Reduced

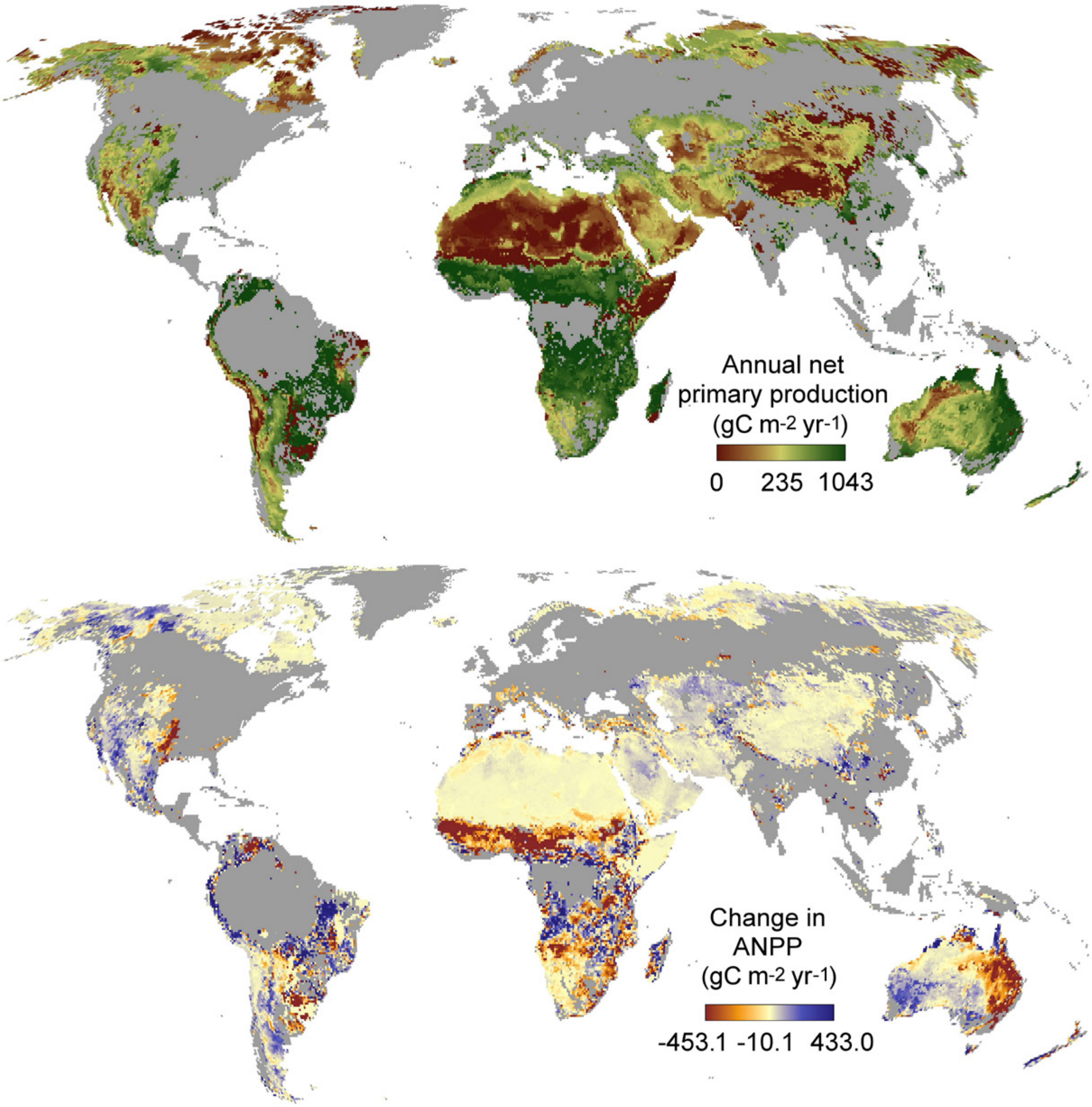

Figure 5.6 | Ensemble simulation results for projected annual net primary productivity of rangelands as simulated in 2000 (top) and their change in 2050 (bottom) under emissions scenario RCP 8.5, with plant responses enhanced by CO$_2$ fertilisation. Results from RCP 4.5 and 8.5, with and without positive effects of atmospheric CO$_2$ on plant production, differed considerably in magnitude but had similar spatial patterns, and so results from RCP 8.5 with increasing production are portrayed spatially here and in other figures. Scale bar labels and the stretch applied to colours are based on the spatial mean value plus or minus two standard deviations (Boone et al. 2017).

forage quality can increase CH$_4$ emissions per unit of gross energy consumed. Increased risk of animal diseases is also an important impact to all production systems (Bett et al. 2017). These depend on the geographical region, land-use type, disease characteristics, and animal susceptibility (Thornton et al. 2009). Also important is the interaction of grazing intensity with climate change. Pfeiffer et al. (2019) estimated that, in a scenario of mean annual precipitation below 500 mm, increasing grazing intensity reduced rangeland productivity and increased annual grass abundance.

Pastoral systems. In Kenya, some 1.8 million extra cattle could be lost by 2030 because of increased drought frequency, the value of the lost animals and production foregone amounting to 630 million USD (Herrero et al. 2010). Martin et al. (2014) assessed impacts of changing precipitation regimes to identify limits of tolerance beyond which pastoral livelihoods could not be secured and found that reduced mean annual precipitation always had negative effects as opposed to increased rainfall variability. Similarly, Martin et al. (2016) found that drought effects on pastoralists in High Atlas in Morocco depended on income needs and mobility options (see Section 5.2.2.6 for additional information about impacts on smallholder farmers).

In summary, observed impacts in pastoral systems include changes in pasture productivity, lower animal growth rates and productivity, damaged reproductive functions, increased pests and diseases, and loss of biodiversity (*high confidence*). Livestock systems are projected to be adversely affected by rising temperatures, depending on the extent of changes in pasture and feed quality, spread of diseases, and water resource availability (*high confidence*). Impacts will differ for different livestock systems and for different regions (*high confidence*). Vulnerability of pastoral systems to climate change is very high (*high confidence*), and mixed systems and industrial or landless livestock systems could encounter several risk factors mainly due to variability of grain availability and cost, and low adaptability of animal genotypes. Pastoral system vulnerability is exacerbated by non-climate factors (land tenure issues, sedentarisation programmes, changes in traditional institutions, invasive species, lack of markets, and conflicts) (*high confidence*).

5.2.2.3 Impacts on pests and diseases

Climate change is changing the dynamics of pests and diseases of both crops and livestock. The nature and magnitude of future changes is likely to depend on local agroecological and management context. This is because of the many biological and ecological mechanisms by which climate change can affect the distribution, population size, and impacts of pests and diseases on food production (Canto et al. 2009; Gale et al. 2009; Thomson et al. 2010; Pangga et al. 2011; Juroszek and von Tiedemann 2013; Bett et al. 2017).

These mechanisms include changes in host susceptibility due to CO_2 concentration effects on crop composition and climate stresses; changes in the biology of pests and diseases or their vectors (e.g., more generational cycles, changes in selection pressure driving evolution); mismatches in timing between pests or vectors and their 'natural enemies'; changes in survival or persistence of pests or disease pathogens (e.g., changes in crop architecture driven by CO_2 fertilisation and increased temperature, providing a more favourable environment for persistence of pathogens like fungi), and changes in pest distributions as their 'climate envelopes' shift. Such processes may affect pathogens, and their vectors, as well as plant, invertebrate and vertebrate pests (Latham et al. 2015).

Furthermore, changes in diseases and their management, as well as changing habitat suitability for pests and diseases in the matrix surrounding agricultural fields, have the ability to reduce or exacerbate impacts (Bebber 2015). For example, changes in water storage and irrigation to adapt to rainfall variation have the potential to enhance disease vector populations and disease occurrence (Bett et al. 2017).

There is *robust evidence* that pests and diseases have already responded to climate change (Bebber et al. 2013), and many studies have now built predictive models based on current incidence of pests, diseases or vectors that indicate how they may respond in future (e.g., Caminade et al. 2015; Kim et al. 2015; Kim and Cho 2016; Samy and Peterson 2016; Yan et al. 2017). Warren et al. (2018) estimate that about 50% of insects, which are often pests or disease vectors, will change ranges by about 50% by 2100 under current GHG emissions trajectories. These changes will lead to crop losses due to changes in insect pests (Deutsch et al. 2018) and weed pressure (Ziska et al. 2018), and thus affect pest and disease management at the farm level (Waryszak et al. 2018). For example, Samy and Peterson (2016) modelled bluetongue virus (BTV), which is spread by biting *Culicodes* midges, finding that the distribution of BTV is likely to be extended, particularly in Central Africa, the USA, and Western Russia.

There is some evidence (*medium confidence*) that exposure will, on average, increase (Bebber and Gurr 2015; Yan et al. 2017), although there are a few examples where changing stresses may limit the range of a vector. There is also a general expectation that perturbations may increase the likelihood of pest and disease outbreaks by disturbing processes that may currently be at some quasi-equilibrium (Canto et al. 2009; Thomson et al. 2010; Pangga et al. 2011). However, in some places, and for some diseases, risks may decrease as well as increase (e.g., drying out may reduce the ability of fungi to survive) (Kim et al. 2015; Skelsey and Newton 2015), or tsetse fly's range may decrease (Terblanche et al. 2008; Thornton et al. 2009).

Pests, diseases, and vectors for both crop and livestock diseases are likely to be altered by climate change (*high confidence*). Such changes are likely to depend on specifics of the local context, including management, but perturbed agroecosystems are more likely, on theoretical grounds, to be subject to pest and disease outbreaks (*low confidence*). Whilst specific changes in pest and disease pressure will vary with geography, farming system, pest/pathogen – increasing in some situations decreasing in others – there is robust evidence, with *high agreement*, that pest and disease pressures are likely to change; such uncertainty requires robust strategies for pest and disease mitigation.

5.2.2.4 Impacts on pollinators

Pollinators play a key role on food security globally (Garibaldi et al. 2016). Pollinator-dependent crops contribute up to 35% of global crop production volume and are important contributors to healthy human diets and nutrition (IPBES 2016). On a global basis, some 1500 crops require pollination (typically by insects, birds and bats) (Klein et al. 2007). Their importance to nutritional security is therefore perhaps under-rated by valuation methodologies, which, nonetheless, include estimates of the global value of pollination services at over 225 billion USD2010 (Hanley et al. 2015). As with other ecosystem processes affected by climate change (e.g., changes in pests and diseases), how complex systems respond is highly context dependent. Thus, predicting the effects of climate on pollination services is difficult (Tylianakis et al. 2008; Schweiger et al. 2010) and uncertain, although there is *limited evidence* that impacts are occurring already (Section 5.2.2.4), and *medium evidence* that there will be an effect.

Pollination services arise from a mutualistic interaction between an animal and a plant – which can be disrupted by climate's impacts on one or the other or both (Memmott et al. 2007). Disruption can occur through changes in species' ranges or by changes in timing of growth stages (Settele et al. 2016). For example, if plant development responds to different cues (e.g., day length) from insects (e.g., temperature), the emergence of insects may not match the flowering times of the plants, causing a reduction in pollination. Climate change will affect pollinator ranges depending on species, life-history, dispersal ability and location. Warren et al. (2018) estimate that under a 3.2°C warming scenario, the existing range of about 49% of insects will be reduced by half by 2100, suggesting either significant range changes (if dispersal occurs) or extinctions (if it does not). However, in principle, ecosystem changes caused by invasions, in some cases, could compensate for the decoupling generated between native pollinators and pollinated species (Schweiger et al. 2010).

Other impacts include changes in distribution and virulence of pathogens affecting pollinators, such as the fungus *Nosema cerana*, which can develop at a higher temperature range than the less-virulent *Nosema apis*; increased mortality of pollinators due to higher frequency of extreme weather events; food shortage for pollinators due to reduction of flowering length and intensity; and aggravation of other threats, such as habitat loss and fragmentation (González-Varo et al. 2013; Goulson et al. 2015; Le Conte and Navajas 2008; Menzel et al. 2006; Walther et al. 2009; IPBES, 2016). The increase in atmospheric CO_2 is also reducing the protein content of pollen, with potential impact on pollination population biology (Ziska et al. 2016).

In summary, as with other complex agroecosystem processes affected by climate change (e.g., changes in pests and diseases), how pollination services respond will be highly context dependent. Thus, predicting the effects of climate on pollination services is difficult and uncertain, although there is *medium evidence* that there will be an effect.

5.2.2.5 Impacts on aquaculture

This report focuses on land-based aquaculture; for assessment of impacts on marine fisheries both natural and farmed see the IPCC Special Report on the ocean and cryosphere in a changing climate (SROCC).

Aquaculture will be affected by both direct and indirect climate change drivers, both in the short and the long-term. Barange et al. (2018) provides some examples of short-term loss of production or infrastructure due to extreme events such as floods, increased risk of diseases, toxic algae and parasites; and decreased productivity due to suboptimal farming conditions. Long-term impacts may include scarcity of wild seed, limited access to freshwater for farming due to reduced precipitation, limited access to feeds from marine and terrestrial sources, decreased productivity due to suboptimal farming conditions, eutrophication and other perturbations.

FAO (2014a) assessed the vulnerability of aquaculture stakeholders to non-climate change drivers, which add to climate change hazards. Vulnerability arises from discrimination in access to inputs and decision-making; conflicts; infrastructure damage; and dependence on global markets and international pressures. Other non-climate drivers identified by McClanahan et al. (2015) include: declining fishery resources; a North–South divide in investment; changing consumption patterns; increasing reliance on fishery resources for coastal communities; and inescapable poverty traps created by low net resource productivity and few alternatives. In areas where vulnerability to climate change is heightened, increased exposure to climate change variables and impacts is likely to exacerbate current inequalities in the societies concerned, penalising further already disadvantaged groups such as migrant fishers (e.g., Lake Chad) or women (e.g., employees in Chile's processing industry) (FAO 2014a).

In many countries the projected declines co-occur across both marine fisheries and agricultural crops (Blanchard et al. 2017), both of which will impact the aquaculture and livestock sectors (Supplementary Material Figure SM5.1). Countries with low Human Development Index, trade opportunities and aquaculture technologies are likely to face greater challenges. These cross-sectoral impacts point to the need for a more holistic account of the inter-connected vulnerabilities of food systems to climate and global change.

5.2.2.6 Impacts on smallholder farming systems

New work has developed farming system approaches that take into account both biophysical and economic processes affected by climate change and multiple activities. Farm households in the developing world often rely on a complex mix of crops, livestock, aquaculture, and non-agricultural activities for their livelihoods (Rosenzweig and Hillel 2015; Antle et al. 2015). Across the world, smallholder farmers are considered to be disproportionately vulnerable to climate change because changes in temperature, rainfall and the frequency or intensity of extreme weather events directly affect their crop and animal productivity as well as their household's food security, income and well-being (Vignola et al. 2015; Harvey et al. 2014b). For example, smallholder farmers in the Philippines, whose survival and livelihood largely depend on the environment, constantly face risks and bear the impacts of the changing climate (Peria et al. 2016).

Smallholder farming systems have been recognised as highly vulnerable to climate change (Morton, 2007) because they are highly dependent on agriculture and livestock for their livelihood (*high confidence*) (Dasgupta et al. 2014). In Zimbabwe, farmers were found vulnerable due to their marginal location, low levels of technology, and lack of other essential farming resources. Farmers observed high frequency and severity of drought; excessive precipitation; drying of rivers, dams and wells; and changes in timing and pattern of seasons as evidence of climate change, and indicated that prolonged wet, hot, and dry weather conditions resulted in crop damage, death of livestock, soil erosion, bush fires, poor plant germination, pests, lower incomes, and deterioration of infrastructure (Mutekwa 2009).

In Madagascar, Harvey et al. (2014b) surveyed 600 small farmers and found that chronic food insecurity, physical isolation and lack of access to formal safety nets increased Malagasy farmers' vulnerability to any shocks to their agricultural system, particularly extreme events. In Chitwan, Nepal, occurrence of extreme events and increased variability in temperature has increased the vulnerability of crops to biotic and abiotic stresses and altered the timing of agricultural operations; thereby affecting crop production (Paudel et al. 2014). In Lesotho, a study on subsistence farming found that food crops were the most vulnerable to weather, followed by soil and livestock. Climate variables of major concern were hail, drought and dry spells which reduced crop yields. In the Peruvian Altiplano, Sietz et al. (2012) evaluated smallholders' vulnerability to weather extremes with regard to food security and found that resource scarcity (livestock, land area), diversification of activities (lack of alternative income, education deprivation) and income restrictions (harvest failure risk) shaped the vulnerability of smallholders. See Section 5.2.2.2 for observed impacts on smallholder pastoral systems.

Projected impacts. By including regional economic models, integrated methods take into account the potential for yield declines to raise prices and thus livelihoods (up to a certain point) in some climate change scenarios. Regional economic models of farming systems can be used to examine the potential for switching to other crops and livestock, as well as the role that non-farm income can play in adaptation (Valdivia et al. 2015 Antle et al. 2015). On the other hand, lost income for smallholders from climate change-related declines (for example, in coffee production), can decrease their food security (Hannah et al. 2017).

Farming system methods developed by AgMIP (Rosenzweig et al. 2013) have been used in regional integrated assessments in Sub-Saharan Africa (Kihara et al. 2015), West Africa (Adiku et al. 2015); East Africa (Rao et al. 2015), South Africa (Beletse et al. 2015), Zimbabwe (Masikati et al. 2015), South Asia (McDermid et al. 2015), Pakistan (Ahmad et al. 2015), the Indo-Gangetic Basin (Subash et al. 2015), Tamil Nadu (Ponnusamy et al. 2015) and Sri Lanka (Zubair et al. 2015). The assessments found that climate change adds pressure to smallholder farmers across Sub-Saharan Africa and South Asia, with winners and losers within each area studied. Temperatures are expected to increase in all locations, and rainfall decreases are projected for the western portion of West Africa and southern Africa, while increases in rainfall are projected for eastern West Africa and all studied regions of South Asia. The studies project that climate change will lead to yield decreases in most study regions except South India and areas in central Kenya, as detrimental temperature effects overcome the positive effects of CO_2.

These studies use AgMIP representative agricultural pathways (RAPs) as a way to involve stakeholders in regional planning and climate resilience (Valdivia et al. 2015). RAPs are consistent with and complement the RCP/SSP approaches for use in agricultural model intercomparisons, improvement, and impact assessments.

New methods have been developed for improving analysis of climate change impacts and adaptation options for the livestock component of smallholder farming systems in Zimbabwe (Descheemaeker et al. 2018). These methods utilised disaggregated climate scenarios, as well as differentiating farms with larger stocking rates compared to less densely stocked farms. By disaggregating climate scenarios, impacts, and smallholder farmer attributes, such assessments can more effectively inform decision-making towards climate change adaptation.

In Central Asia, a study using the bio-economic farm model (BEFM) found large differences in projected climate change impact ranging from positive income gains in large-scale commercial farms in contrast to negative impacts in small-scale farms (Bobojonov and Aw-Hassan 2014). Negative impacts may be exacerbated if irrigation water availability declines due to climate change and increased water demand in upstream regions. In Iran, changes in rainfall and water endowments are projected to significantly impact crop yield and water requirements, as well as income and welfare of farm families (Karimi et al. 2018).

Climate change impacts on food, feed and cash crops other than cereals, often grown in smallholder systems or family farms are less often studied, although impacts can be substantial. For example, areas suitable for growing coffee are expected to decrease by 21% in Ethiopia with global warming of 2.4°C (Moat et al. 2017) and more than 90% in Nicaragua (Läderach et al. 2017) with 2.2°C local temperature increase.

Climate change can modify the relationship between crops and livestock in the landscape, affecting mixed crop-livestock systems in many places. Where crop production will become marginal, livestock may provide an alternative to cropping. Such transitions could occur in up to 3% of the total area of Africa, largely as a result of increases in the probability of season failure in the drier mixed crop–livestock systems of the continent (Thornton et al. 2014).

In Mexico, subsistence agriculture is expected to be the most vulnerable to climate change, due to its intermittent production and reliance on maize and beans (Monterroso et al. 2014). Overall, a decrease in suitability and yield is expected in Mexico and Central America for beans, coffee, maize, plantain and rice (Donatti et al. 2018). Municipalities with a high proportional area under subsistence crops in Central America tend to have less resources to promote innovation and action for adaptation (Bouroncle et al. 2017).

In summary, smallholder farmers are especially vulnerable to climate change because their livelihoods often depend primarily on agriculture. Further, smallholder farmers often suffer from chronic food insecurity (*high confidence*). Climate change is projected to exacerbate risks of pests and diseases and extreme weather events in smallholder farming systems.

5.2.3 Climate change impacts on access

Access to food involves the ability to obtain food, including the ability to purchase food at affordable prices.

5.2.3.1 Impacts on prices and risk of hunger

A protocol-based analysis based on AgMIP methods tested a combination of RCPs and SSPs to provide a range of projections for prices, risk of hunger, and land-use change (Hasegawa et al. 2018) (Figure 5.7 and Supplementary Material Table SM5.4.). Previous studies have found that decreased agricultural productivity will depress agricultural supply, leading to price increases. Despite different economic models with various representations of the global food system (Valin et al. 2014; Robinson et al. 2014; Nelson et al. 2013; Schmitz et al. 2014), as well as having represented the SSPs in different ways, for example, technological change, land-use policies, and sustainable diets (Stehfest et al. 2019; Hasegawa et al. 2018),

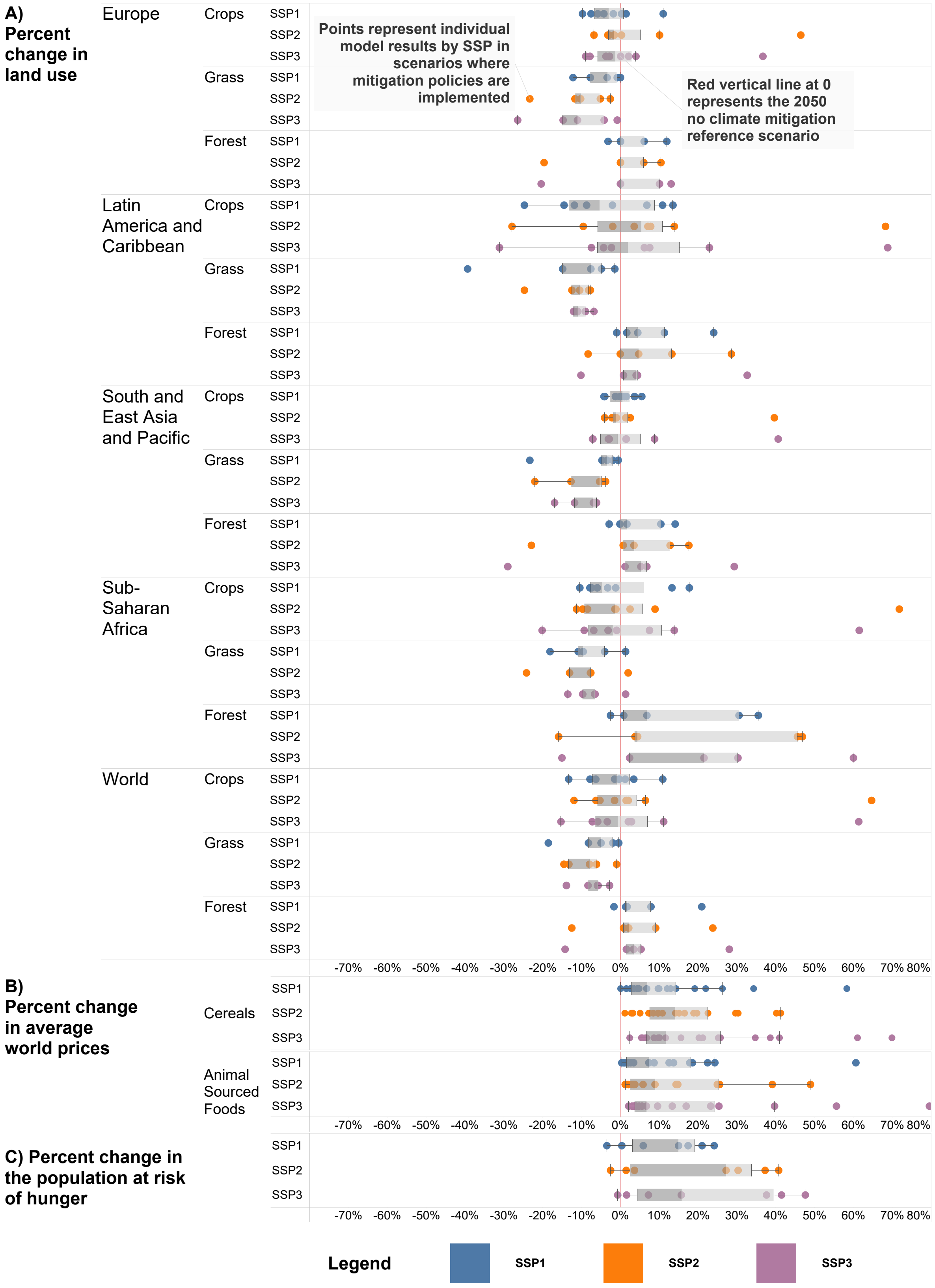

Figure 5.7 | Implications of climate change by 2050 on land-use, selected agricultural commodity prices, and the population at risk of hunger based on AgMIP Global Economic Model analysis. (A) Projected % change in land-use by 2050 by land type (cropland, grassland, and forest) and SSP. **(B)** Projected % changes in average world prices by 2050 for cereals (rice, wheat, and coarse grains) and animal sourced foods (ruminant meat, monogastric, and dairy) by SSP. **(C)** Percentage change by 2050 in the global population at risk of hunger by SSP. (Hasegawa et al. 2018).

the ensemble of participating models projected a 1–29% cereal price increase in 2050 across SSPs 1, 2 and 3 due to climate change (RCP 6.0). This would impact consumers globally through higher food prices, though regional effects will vary. The median cereal price increase was 7%, given current projections of demand. In all cases (across SSPs and global economic models), prices are projected to increase for rice and coarse grains, with only one instance of a price decline (–1%) observed for wheat in SSP1, with price increases projected in all other cases. Animal-sourced foods (ASFs) are also projected to see price increases (1%), but the range of projected price changes are about half those of cereals, highlighting that the climate impacts on ASFs will be felt indirectly, through the cost and availability of feed, and that there is significant scope for feed substitution within the livestock sector.

Declining food availability caused by climate change is likely to lead to increasing food cost impacting consumers globally through higher prices and reduced purchasing power, with low-income consumers particularly at risk from higher food prices (Nelson et al. 2010; Springmann et al. 2016a and Nelson et al. 2018). Higher prices depress consumer demand, which in turn will not only reduce energy intake (calories) globally (Hasegawa et al. 2015; Nelson et al. 2010; Springmann et al. 2016a and Hasegawa et al. 2018), but will also likely lead to less healthy diets with lower availability of key micronutrients (Nelson et al. 2018) and increase diet-related mortality in lower and middle-income countries (Springmann et al. 2016a). These changes will slow progress towards the eradication of malnutrition in all its forms.

The extent that reduced energy intake leads to a heightened risk of hunger varies by global economic model. However, all models project an increase in the risk of hunger, with the median projection of an increase in the population at risk of insufficient energy intake by 6, 14, and 12% in 2050 for SSPs 1, 2 and 3 respectively compared to a no climate change reference scenario. This median percentage increase would be the equivalent of 8, 24 and 80 million (full range 1–183 million) additional people at risk of hunger due to climate change (Hasegawa et al. 2018).

5.2.3.2 Impacts on land use

Climate change is likely to lead to changes in land use globally (Nelson et al. 2014; Schmitz et al. 2014 and Wiebe et al. 2015). Hasegawa et al. (2018) found that declining agricultural productivity broadly leads to the need for additional cropland, with 7 of 8 models projecting increasing cropland and the median increase by 2050 projected across all models of 2% compared to a no climate change reference (Figure 5.7). Not all regions will respond to climate impacts equally, with more uncertainty on regional land-use change across the model ensemble than the global totals might suggest. For example, the median land-use change for Latin America is an increase of cropland by 3%, but the range across the model ensemble is significant, with three models projecting declines in cropland (–25 to –1%) compared to the five models projecting cropland increase (0–5%). For further discussion on land-use change and food security see Section 5.6.

5.2.4 Climate change impacts on food utilisation

Food utilisation involves nutrient composition of food, its preparation, and overall state of health. Food safety and quality affects food utilisation.

5.2.4.1 Impacts on food safety and human health

Climate change can influence food safety through changing the population dynamics of contaminating organisms due to, for example, changes in temperature and precipitation patterns, humidity, increased frequency and intensity of extreme weather events, and changes in contaminant transport pathways. Changes in food and farming systems, for example, intensification to maintain supply under climate change, may also increase vulnerabilities as the climate changes (Tirado et al. 2010).

Climate-related changes in the biology of contaminating organisms include changing the activity of mycotoxin-producing fungi, changing the activity of microorganisms in aquatic food chains that cause disease (e.g., dinoflagellates, bacteria like *Vibrio*), and increasingly heavy rainfall and floods causing contamination of pastures with enteric microbes (like *Salmonella*) that can enter the human food chain. Degradation and spoilage of products in storage and transport can also be affected by changing humidity and temperature outside of cold chains, notably from microbial decay but also from potential changes in the population dynamics of stored product pests (e.g., mites, beetles, moths) (Moses et al. 2015).

Mycotoxin-producing fungi occur in specific conditions of temperature and humidity, so climate change will affect their range, increasing risks in some areas (such as mid-temperate latitudes) and reducing them in others (e.g., the tropics) (Paterson and Lima 2010). There is *robust evidence* from process-based models of particular species (*Aspergillus*/Aflatoxin B1, *Fusarium*/deoxynivalenol), which include projections of future climate that show that aflatoxin contamination of maize in Southern Europe will increase significantly (Battilani et al. 2016), and deoxynivalenol contamination of wheat in Northwestern Europe will increase by up to three times current levels (van der Fels-Klerx et al. 2012b, a).

Whilst downscaled climate models make any specific projection for a given geography uncertain (Van der Fels-Klerx et al. 2013), experimental evidence on the small scale suggests that the combination of rising CO_2 levels, affecting physiological processes in photosynthetic organisms, and temperature changes, can be significantly greater than temperature alone (Medina et al. 2014). Risks related to aflatoxins are likely to change, but detailed projections are difficult because they depend on local conditions (Vaughan et al. 2016).

Foodborne pathogens in the terrestrial environment typically come from enteric contamination (from humans or animals), and can be spread by wind (blowing contaminated soil) or flooding – the incidence of both of which are likely to increase with climate change (Hellberg and Chu 2016). Furthermore, water stored for irrigation, which may be increased in some regions as an adaptation strategy, can become an important route for the spread of pathogens (as well as other pollutants). Contaminated water and diarrheal diseases are acute threats to food security (Bond et al. 2018). Whilst there is little direct evidence (in terms of modelled projections) the results of a range of reviews, as well as expert groups, suggest that risks from foodborne pathogens are likely to increase through multiple mechanisms (Tirado et al. 2010; van der Spiegel et al. 2012; Liu et al. 2013; Kirezieva et al. 2015; Hellberg and Chu 2016).

An additional route to climate change impacts on human health can arise from the changing biology of plants altering human exposure levels. This may include climate changing how crops sequester heavy metals (Rajkumar et al. 2013), or how they respond to changing pest pressure (e.g., cassava produces hydrogen cyanide as a defence against herbivore attack).

All of these factors will lead to regional differences regarding food safety impacts (Paterson and Lima 2011). For instance, in Europe it is expected that most important food safety-related impacts will be mycotoxins formed on plant products in the field or during storage; residues of pesticides in plant products affected by changes in pest pressure; trace elements and/or heavy metals in plant products depending on changes in abundance and availability in soils; polycyclic aromatic hydrocarbons in foods following changes in long-range atmospheric transport and deposition; and presence of pathogenic bacteria in foods following more frequent extreme weather, such as flooding and heat waves (Miraglia et al. 2009).

In summary, there is *medium evidence*, with *high agreement* that food utilisation via changes in food safety (and potentially food access from food loss) will be impacted by climate change, mostly by increasing risks, but there is *low confidence*, exactly how they may change for any given place.

5.2.4.2 Impacts on food quality

There are two main routes by which food quality may change. First, the direct effects of climate change on plant and animal biology, such as through changing temperatures changing the basic metabolism of plants. Secondly, by increasing carbon dioxide's effect on biology through CO_2 fertilisation.

Direct effects on plant and animal biology. Climate affects a range of biological processes, including the metabolic rate in plants and ectothermic animals. Changing these processes can change growth rates, and therefore yields, but can also cause organisms to change relative investments in growth vs reproduction, and therefore change the nutrients assimilated. This may decrease protein and mineral nutrient concentrations, as well as alter lipid composition (DaMatta et al. 2010). For example, apples in Japan have been exposed to higher temperatures over 3–4 decades and have responded by blooming earlier. This has led to changes in acidity, firmness, and water content, reducing quality (Sugiura et al. 2013). In other fruit, such as grapes, warming-induced changes in sugar composition affect both colour and aroma (Mira de Orduña 2010). Changing heat stress in poultry can affect yield as well as meat quality (by altering fat deposition and chemical constituents), shell quality of eggs, and immune systems (Lara and Rostagno 2013).

Effects of rising CO_2 concentrations. Climate change is being driven by rising concentrations of carbon dioxide and other GHG's in the atmosphere. As plants use CO_2 in photosynthesis to form sugar, rising CO_2 levels, all things being equal, enhances the process unless limited by water or nitrogen availability. This is known as 'CO_2 fertilisation'. Furthermore, increasing CO_2 allows stomata to partially close during gas exchange, reducing water loss through transpiration. These two factors affect the metabolism of plants, and, as with changing temperatures, affects plant growth rates, yields and their nutritional quality. Studies of these effects include meta-analyses, modelling, and small-scale experiments (Franzaring et al. 2013; Mishra and Agrawal 2014; Myers et al. 2014; Ishigooka et al. 2017; Zhu et al. 2018; Loladze 2014 and Yu et al. 2014).

With regard to nutrient quality, a meta-analysis from seven Free-Air Carbon dioxide Enrichment (FACE), (with elevated atmospheric CO_2 concentration of 546–586 ppm) experiments (Myers et al. 2014), found that wheat grains had 9.3% lower zinc (CI 5.9–12.7%), 5.1% lower iron (CI 3.7–6.5%) and 6.3% lower protein (CI 5.2–7.5%), and rice grains had 7.8% lower protein content (CI 6.8–8.9%). Changes in nutrient concentration in field pea, soybean and C4 crops such as sorghum and maize were small or insignificant. Zhu et al. (2018) report a meta-analysis of FACE trials on a range of rice cultivars. They show that protein declines by an average of 10% under elevated CO_2, iron and zinc decline by 8% and 5% respectively. Furthermore, a range of vitamins show large declines across all rice cultivars, including B1 (–17%), B2 (–17%), B5 (–13%) and B9 (–30%), whereas vitamin E increased. As rice underpins the diets of many of the world's poorest people in low-income countries, especially in Asia, Zhu et al. (2018) estimate that these changes under high CO_2 may affect the nutrient status of about 600 million people.

Decreases in protein concentration with elevated CO_2 are related to reduced nitrogen concentration possibly caused by nitrogen uptake not keeping up with biomass growth, an effect called 'carbohydrate dilution' or 'growth dilution', and by inhibition of photorespiration which can provide much of the energy used for assimilating nitrate into proteins (Bahrami et al. 2017). Other mechanisms have also been postulated (Feng et al. 2015; Bloom et al. 2014; Taub and Wang 2008). Together, the impacts on protein availability may take as many as 150 million people into protein deficiency by 2050 (Medek et al. 2017). Legume and vegetable yields increased with elevated CO_2 concentration of 250 ppm above ambient by 22% (CI 11.6–32.5%), with a stronger effect on leafy vegetables than on legumes and no impact for changes in iron, vitamin C or flavonoid concentration (Scheelbeek et al. 2018).

Increasing concentrations of atmospheric CO_2 lower the content of zinc and other nutrients in important food crops. Dietary deficiencies of zinc and iron are a substantial global public health problem (Myers et al. 2014). An estimated two billion people suffer these deficiencies (FAO 2013a), causing a loss of 63 million life-years annually (Myers et al. 2014). Most of these people depend on C3 grain legumes as their primary dietary source of zinc and iron. Zinc deficiency is currently responsible for large burdens of disease globally, and the populations who are at highest risk of zinc deficiency receive most of their dietary zinc from crops (Myers et al. 2015). The total number of people estimated to be placed at new risk of zinc deficiency by 2050 is 138 million. The people likely to be most affected live in Africa and South Asia, with nearly 48 million residing in India alone. Differences between cultivars of a single crop suggest that breeding for decreased sensitivity to atmospheric CO_2 concentration could partly address these new challenges to global health (Myers et al. 2014).

In summary, while increased CO_2 is projected to be beneficial for crop productivity at lower temperature increases, it is projected to lower nutritional quality (e.g., less protein, zinc, and iron) (*high confidence*).

5.2.5 Climate change impacts on food stability

Food stability is related to people's ability to access and use food in a steady way, so that there are not intervening periods of hunger. Increasing extreme events associated with climate change can disrupt food stability (see Section 5.8.1 for assessment of food price spikes).

5.2.5.1 Impacts of extreme events

FAO et al. (2018) conducted an analysis of the prevalence of undernourishment (PoU) and found that in 2017, the average of the PoU was 15.4% for all countries exposed to climate extremes (Supplementary Material Figure SM5.2). At the same time, the PoU was 20% for countries that additionally show high vulnerability of agriculture production/yields to climate variability, or 22.4% for countries with high PoU vulnerability to severe drought. When there is both high vulnerability of agriculture production/yields and high PoU sensitivity to severe drought, the PoU is 9.8 points higher (25.2%). These vulnerabilities were found to be higher when countries had a high dependence on agriculture as measured by the number of people employed in the sector. Bangkok experienced severe flooding in 2011–2012 with large-scale disruption of the national food supply chains since they were centrally organised in the capital city (Allen et al. 2017).

The IPCC projects that frequency, duration, and intensity of some extreme events will increase in the coming decades (IPCC 2018a, 2012). To test these effects on food security, Tigchelaar et al. (2018) showed rising instability in global grain trade and international grain prices, affecting especially the about 800 million people living in extreme poverty who are most vulnerable to food price spikes (Section 5.8.1). They used global datasets of maize production and climate variability combined with future temperature projections to quantify how yield variability will change in the world's major maize-producing and exporting countries under 2°C and 4°C of global warming.

Tesfaye et al. (2017) projected that the extent of heat-stressed areas in South Asia could increase by up to 12% in 2030 and 21% in 2050 relative to the baseline (1950–2000). Another recent study found that drier regions are projected to dry earlier, more severely and to a greater extent than humid regions, with the population of Sub-Saharan Africa most vulnerable (Lickley and Solomon 2018).

5.2.5.2 Food aid

Food aid plays an important role in providing food security and saving lives after climate disasters. In 2015, 14.5 million people were assisted through disaster-risk reduction, climate change and/or resilience building activities (WFP 2018). However, there is no agreement on how to better use emergency food aid, since it can come with unintended consequences for individuals, groups, regions, and countries (Barrett 2006). These may include negative dependency of food recipients (Lentz et al. 2005) or price increases, among others.

Some authors state that tied food aid provided as 'in kind' by the donor country hampers local food production (Clay 2006), although others found no evidence of this (Ferrière and Suwa-Eisenmann 2015). Untied cash aid can be used to buy food locally or in neighbouring countries, which is cheaper and can contribute to improving the livelihoods of local farmers (Clay 2006).

Ahlgren et al. (2014) found that food aid dependence of Marshall Islands due to climate change impacts can result in poor health outcomes due to the poor nutritional quality of food aid, which may result in future increases of chronic diseases. In this regard, Mary et al. (2018) showed that nutrition-sensitive aid can reduce the prevalence of undernourishment.

In summary, based on AR5 and SR15 assessments that the likelihood of extreme weather events will increase, (e.g., increases in heatwaves, droughts, inland flooding, and coastal flooding due to rising sea levels, depending on region) in both frequency and magnitude, decreases in food stability and thus increases in food insecurity will likely rise as well (*medium evidence, high agreement*).

5.3 Adaptation options, challenges and opportunities

This section assesses the large body of literature on food system adaptation to climate change, including increasing extreme events, within a framework of autonomous, incremental, and transformational adaptation. It focuses primarily on regional and local considerations and adaptation options for both the supply side (production, storage, transport, processing, and trade) and the demand side (consumption and diets) of the food system. Agroecological, social, and cultural contexts are considered throughout. Finally, the section assesses the role of institutional measures at global, regional (multiple countries), national, and local scales and capacity-building.

5.3.1 Challenges and opportunities

By formulating effective adaptation strategies, it is possible to reduce or even avoid some of the negative impacts of climate change on food security (Section 5.2). However, if unabated climate change continues, limits to adaptation will be reached (SR15). In the food system, adaptation actions involve any activities designed to reduce vulnerability and enhance resilience of the system to climate change. In some areas, expanded climate envelopes will alter agroecological zones, with opportunity for expansion towards higher latitudes and altitudes, soil and water resources permitting (Rosenzweig and Hillel 2015).

More extreme climatic events are projected to lead to more agrometeorological disasters with associated economic and social losses. There are many options for adapting the food system to extreme events reported in IPCC (2012), highlighting measures that reduce exposure and vulnerability and increase resilience, even though risks cannot fully be eliminated (IPCC 2012). Adaptation responses to extreme events aim to minimise damages, modify threats, prevent adverse impacts, or share losses, thus making the system more resilient (Harvey et al. 2014a).

With current and projected climate change (higher temperature, changes in precipitation, flooding and extremes events), achieving adaptation will require both technological (e.g., recovering and improving orphan crops, new cultivars from breeding or biotechnology) and non-technological (e.g., markets, land management, dietary change) solutions. Climate interacts with other factors such as food supplied over longer distances and policy drivers (Mbow et al. 2008; Howden et al. 2007), as well as local agricultural productivity.

Given the site-specific nature of climate change impacts on food system components together with wide variation in agroecosystems types and management, and socio-economic conditions, it is widely understood that adaptation strategies are linked to environmental and cultural contexts at the regional and local levels (*high confidence*). Developing systemic resilience that integrates climate drivers with social and economic drivers would reduce the impact on food security, particularly in developing countries. For example, in Africa, improving food security requires evolving food systems to be highly climate resilient, while supporting the need for increasing yield to feed the growing population (Mbow et al. 2014b) (Box 5.2).

Adaptation involves producing more food where needed, moderating demand, reducing waste, and improving governance (Godfray and Garnett 2014) (see Section 5.6 for the significant synergies between adaptation and mitigation through specific practices, actions and strategies).

Box 5.2 | Sustainable solutions for food systems and climate change in Africa

Climate change, land-use change, and food security are important aspects of sustainability policies in Africa. According to the McKinsey Global Institute (2010), Africa has around 60% of the global uncultivated arable land; thus the continent has a high potential for transformative change in food production. With short and long-term climate change impacts combined with local poverty conditions, land degradation and poor farming practices, Africa cannot grow enough food to feed its rapidly growing population. Sustainable improvement of productivity is essential, even as the impacts of climate change on food security in Africa are projected to be multiple and severe.

Sustainable Land Management (SLM) of farming systems is important to address climate change while dealing with these daunting food security needs and the necessity to improve access to nutritious food to maintain healthy and active lives in Africa (AGRA 2017). SLM has functions beyond the production of food, such as delivery of water, protection against disease (especially zoonotic diseases), the delivery of energy, fibre and building materials.

Commodity-based systems – driven by external markets – are increasing in Africa (cotton, cocoa, coffee, palm oil, groundnuts) with important impacts on the use of land and climate. Land degradation, decreasing water resources, loss of biodiversity, excessive use of synthetic fertilisers and pesticides are some of the environmental challenges that influence preparedness to adapt to climate change (Pretty and Bharucha 2015). A balanced strategy on African agriculture can be based on SLM and multifunctional land-use approaches combining food production, cash crops, ecosystem services, biodiversity conservation, ecosystem services delivery, and ILK.

Figure 5.8 | Factors influencing sustainable food systems in Africa.

Box 5.2 (continued)

Thus, sustainable food systems in Africa entail multiple dimensions as shown in Figure 5.8.

With rapid urbanisation, it is important to integrate strategies (e.g., zero-carbon energy, smart irrigation systems, and climate-resilient agriculture) to minimise the negative effects of climate change while securing quality food for a growing population.

Building resilience into productivity and production can be based on simultaneous attention to the following five overarching issues:

1. Closing yield gaps through adapted cultivars, sustainable land management combining production and preservation of ecosystems essential functions, such as sustainable intensification approaches based on conservation agriculture and community-based adaptation with functioning support services and market access (Mbow et al. 2014a).
2. Identifying sustainable land management practices (agroecology, agroforestry, etc.) addressing different ecosystem services (food production, biodiversity, reduction of GHG emissions, soil carbon sequestration) for improved land-based climate change adaptation and mitigation (Sanz et al. 2017; Francis 2016).
3. Paying attention to the food-energy-water nexus, especially water use and reutilisation efficiency but also management of rainwater (Albrecht et al. 2018).
4. Implementing institutional designs focused on youth and women through new economic models that help enable access to credit and loans to support policies that balance cash and food crops.
5. Building on local knowledge, culture and traditions while seeking innovations for food waste reduction and transformation of agricultural products.

These aspects suppose both incremental and transformational adaptation that may stem from better infrastructure (storage and food processing), adoption of harvest and post-harvest technologies that minimise food waste, and development of new opportunities for farmers to respond to environmental, economic and social shocks that affect their livelihoods (Morton 2017).

Agriculture in Africa offers a unique opportunity for merging adaption to and mitigation of climate change with sustainable production to ensure food security (CCAFS 2012; FAO 2012). Initiatives throughout the food system on both the supply and demand sides can lead to positive outcomes.

5.3.2 Adaptation framing and key concepts

5.3.2.1 Autonomous, incremental, and transformational adaptation

Framing of adaptation in this section categorises and assesses adaptation measures as autonomous, incremental, and transformational (Glossary and Table 5.3). Adaptation responses can be reactive or anticipatory.

Autonomous. Autonomous adaptation in food systems does not constitute a conscious response to climatic stimuli but is triggered by changes in agroecosystems, markets, or welfare changes. It is also referred to as spontaneous adaptation (IPCC 2007). Examples of autonomous adaptation of rural populations have been documented in the Sahel (IRD 2017). In India, farmers are changing sowing and harvesting timing, cultivating short duration varieties, inter-cropping, changing cropping patterns, investing in irrigation, and establishing agroforestry. These are considered as passive responses or autonomous adaptation, because they do not acknowledge that these steps are taken in response to perceived climatic changes (Tripathi and Mishra 2017).

Incremental. Incremental adaptation maintains the essence and integrity of a system or process at a given scale (Park et al. 2012). Incremental adaptation focuses on improvements to existing resources and management practices (IPCC 2014a).

Transformational. Transformational adaptation changes the fundamental attributes of a socio-ecological system either in anticipation of, or in response to, climate change and its impacts (IPCC 2014a). Transformational adaptation seeks alternative livelihoods and land-use strategies needed to develop new farming systems (Termeer et al. 2016). For example, limitations in incremental adaptation among smallholder rice farmers in Northwest Costa Rica led to a shift from rice to sugarcane production due to decreasing market access and water scarcity (Warner et al. 2015). Migration from the Oldman River Basin has been described as a transformational adaption to climate change in the Canadian agriculture sector (Hadarits et al. 2017). If high-end scenarios of climate change eventuate, the food security of farmers and consumers will depend on how transformational change in food systems is managed. An integrated framework of adaptive transition – management of socio-technical transitions and adaptation to socio-ecological changes – may help build transformational adaptive capacity

Table 5.3 | Synthesis of food security related adaptation options to address climate risks (IPCC 2014b; Vermeulen et al. 2013, 2018; Burnham and Ma 2016; Bhatta and Aggarwal 2016).

Key climate drivers and risks	Incremental adaptation	Transformational adaptation	Enabling conditions
– Extreme events and short-term climate variability – Stress on water resources, drought stress, dry spells, heat extremes, flooding, shorter rainy seasons, pests	– Change in variety, water management, water harvesting, supplemental irrigation during dry spells – Planting dates, pest control, feed banks – Transhumance, other sources of revenue (e.g., charcoal, wild fruits, wood, temporary work) – Soil management, composting	– Early Warning Systems – Planning for and prediction of seasonal to intra-seasonal climate risks to transition to safer food conditions – Abandonment of monoculture, diversification – Crop and livestock insurance – Alternate cropping, intercropping – Erosion control	– Establishment of climate services – Integrated water management policies, integrated land and water governance – Seed banks, seed sovereignty and seed distribution policies – Capacity building and extension programmes
– Warming trend, drying trend – Reduced crop productivity due to persistent heat, long drought cycles, deforestation and land degradation with strong adverse effects on food production and nutrition quality, increased pest and disease damage	– Strategies to reduce effects of recurring food challenges – Sustainable intensification, agroforestry, conservation agriculture, SLM – Adoption of existing drought-tolerant crop and livestock species – Counter season crop production – Livestock fattening – New ecosystem-based adaptation (e.g., bee keeping, woodlots) – Farmers management of natural resources – Labour redistribution (e.g., mining, development projects, urban migration) – Adjustments to markets and trade pathways already in place	– Climate services for new agricultural programmes (e.g., sustainable irrigation districts) – New technology (e.g., new farming systems, new crops and livestock breeds) – Switches between cropping and transhumant livelihoods, replacement of pasture or forest to irrigated/rainfed crops – Shifting to small ruminants or drought resistant livestock or fish farming – Food storage infrastructures, food transformation – Changes in cropping area, land rehabilitation (enclosures, afforestation) perennial farming – New markets and trade pathways	– Climate information in local development policies – Stallholders' access to credit and production resources – National food security programme based on increased productivity, diversification, transformation and trade – Strengthening (budget, capacities, expertise) of local and national institutions to support agriculture and livestock breeding – Devolution to local communities, women's empowerment, market opportunities – Incentives for establishing new markets and trade pathways

(Mockshell and Kamanda 2018 and Pant et al. 2015). Rippke et al. (2016) has suggested overlapping phases of adaptation needed to support transformational change in Africa.

5.3.2.2 Risk management

Climate risks affect all pillars of food security, particularly stability because extreme events lead to strong variation to food access. The notion of risk is widely treated in IPCC reports (IPCC 2014c) (see also Chapter 7 in this report). With food systems, many risks co-occur or reinforce each other, and this can limit effective adaptation planning as they require a comprehensive and dynamic policy approach covering a range of drivers and scales. For example, from the understanding by farmers of change in risk profiles to the establishment of efficient markets that facilitate response strategies will require more than systemic reviews of risk factors (Howden et al. 2007).

Integration of Climate Change Adaptation (CCA) and Disaster Risk Reduction (DRR) helps to minimise the overlap and duplication of projects and programmes (Nalau et al. 2016). Recently, countries started integrating the concept of DRR and CCA. For instance, the Philippines introduced new legislation calling for CCA and DRR integration, as current policy instruments had been largely unsuccessful in combining agencies and experts across the two areas (Leon and Pittock 2016).

Studies reveal that the amplitude of interannual growing-season temperature variability is in general larger than that of long-term temperature change in many locations. Responding better to seasonal climate-induced food supply shocks therefore increases society's capability to adapt to climate change. Given these backgrounds, seasonal crop forecasting and early response recommendations (based on seasonal climate forecasts), are emerging to strengthen existing operational systems for agricultural monitoring and forecasting (FAO 2016a; Ceglar et al. 2018 and Iizumi et al. 2018).

While adaptation and mitigation measures are intended to reduce the risk from climate change impacts in food systems, they can also be sources of risk themselves (e.g., investment risk, political risk) (IPCC 2014b). Climate-related hazards are a necessary element of risks related to climate impacts but may have little or nothing to do with risks related to some climate policies/responses.

Adoption of agroecological practices could provide resilience for future shocks, spread farmer risk and mitigate the impact of droughts (Niles et al. 2018) (Section 5.3.2.3). Traditionally, risk management is performed through multifunctional landscape approaches in which resource utilisation is planned across wide areas and local agreements on resource access. Multifunctionality permits vulnerable communities to access various resources at various times and under various risk conditions (Minang et al. 2015).

In many countries, governmental compensation for crop-failure and financial losses are used to protect against risk of severe yield reductions. Both public and private sector groups develop insurance markets and improve and disseminate index-based weather insurance programmes. Catastrophe bonds, microfinance, disaster contingency funds, and cash transfers are other available mechanisms for risk management.

In summary, risk management can be accomplished through agroecological landscape approaches and risk sharing and transfer mechanisms, such as development of insurance markets and improved index-based weather insurance programmes (*high confidence*).

5.3.2.3 Role of agroecology and diversification

Agroecological systems are integrated land-use systems that maintain species diversity in a range of productive niches. Diversified cropping systems and practicing traditional agroecosystems of crop production where a wide range of crop varieties are grown in various spatial and temporal arrangements, are less vulnerable to catastrophic loss (Zhu et al. 2011). The use of local genetic diversity, soil organic matter enhancement, multiple-cropping or poly-culture systems, home gardening, and agroecological approaches can build resilience against extreme climate events (Altieri and Koohafkan 2008).

However, Nie et al. (2016) argued that while integrated crop-livestock systems present some opportunities such as control of weeds, pests and diseases, and environmental benefits, there are some challenges, including yield reduction, difficulty in pasture-cropping, grazing, and groundcover maintenance in high rainfall zones, and development of persistent weeds and pests.

Adaptation measures based on agroecology entail enhancement of agrobiodiversity; improvement of ecological processes and delivery of ecosystem services. They also entail strengthening of local communities and recognition of the role and value of ILK. Such practices can enhance the sustainability and resilience of agricultural systems by buffering climate extremes, reducing degradation of soils, and reversing unsustainable use of resources; outbreak of pests and diseases and consequently increase yield without damaging biodiversity. Increasing and conserving biological diversity such as soil microorganisms can promote high crop yields and sustain the environment (Schmitz et al. 2015; Bhattacharyya et al. 2016; Garibaldi et al. 2017).

Diversification of many components of the food system is a key element for increasing performance and efficiency that may translate into increased resilience and reduced risks (integrated land management systems, agrobiodiversity, ILK, local food systems, dietary diversity, the sustainable use of indigenous fruits, neglected and underutilised crops as a food source) (*medium confidence*) (Makate et al. 2016; Lin 2011; Awodoyin et al. 2015).

The more diverse the food systems are, the more resilient they are in enhancing food security in the face of biotic and abiotic stresses. Diverse production systems are important for providing regulatory ecosystem services such as nutrient cycling, carbon sequestration, soil erosion control, reduction of GHG emissions and control of hydrological processes (Chivenge et al. 2015). Further options for adapting to change in both mean climate and extreme events are livelihood diversification (Michael 2017; Ford et al. 2015), and production diversity (Sibhatu et al. 2015).

Crop diversification, maintaining local genetic diversity, animal integration, soil organic matter management, water conservation, and harvesting the role of microbial assemblages. These types of farm management significantly affect communities in soil, plant structure, and crop growth in terms of number, type, and abundance of species (Morrison-Whittle et al. 2017). Complementary strategies towards sustainable agriculture (ecological intensification, strengthening existing diverse farming systems and investment in ecological infrastructure) also address important drivers of pollinator decline (IPBES 2016).

Evidence also shows that, together with other factors, on-farm agricultural diversity can translate into dietary diversity at the farm level and beyond (Pimbert and Lemke 2018; Kumar et al. 2015; Sibhatu et al. 2015). Dietary diversity is important but not enough as an adaptation option, but results in positive health outcomes by increasing the variety of healthy products in people's diets and reducing exposure to unhealthy environments.

Locally developed seeds and the concept of seed sovereignty can both help protect local agrobiodiversity and can often be more climate resilient than generic commercial varieties (Wattnem 2016; Coomes et al. 2015; van Niekerk and Wynberg 2017; Vasconcelos et al. 2013). Seed exchange networks and banks protect local agrobiodiversity and landraces, and can provide crucial lifelines when crop harvests fail (Coomes et al. 2015; van Niekerk and Wynberg 2017; Vasconcelos et al. 2013).

Related to locally developed seeds, neglected and underutilised species (NUS) can play a key role in increasing dietary diversity (*high confidence*) (Baldermann et al. 2016; van der Merwe et al. 2016; Kahane et al. 2013; Muhanji et al. 2011) (Box 5.3). These species can also improve nutritional and economic security of excluded social groups, such as tribals (Nandal and Bhardwaj 2014; Ghosh-Jerath et al. 2015), indigent (Kucich and Wicht 2016) or rural populations (Ngadze et al. 2017).

Dietary diversity has also been correlated (*medium evidence, medium agreement*) to agricultural diversity in small-holder and subsistence farms (Ayenew et al. 2018; Jones et al. 2014; Jones 2017; Pimbert and Lemke 2018), including both crops and animals, and has been proposed as a strategy to reduce micronutrient malnutrition in developing countries (Tontisirin et al. 2002). In this regard, the capacity of subsistence farming to supply essential nutrients in reasonable balance to the people dependent on them has been considered as a means of overcoming their nutrient limitations in sound agronomic and sustainable ways (Graham et al. 2007).

Ecosystem-based adaptation (EbA). EbA is a set of nature-based methods addressing climate change adaptation and food security by strengthening and conserving natural functions, goods and services that benefit people. EbA approaches to address food security provide co-benefits such as contributions to health and improved diet, sustainable land management, economic revenue and water security. EbA practices can reduce GHG emissions and increase carbon storage (USAID 2017).

Box 5.3 | Climate change and indigenous food systems in the Hindu-Kush Himalayan Region

Diversification of production systems through promotion of Neglected and Underutilised Species (NUS; also known as understudied, neglected, orphan, lost or disadvantaged crops) offers adaptation opportunities to climate change, particularly in mountains. Neglected and Underutilised Species (NUS) have a potential to improve food security and at the same time help protect and conserve traditional knowledge and biodiversity. Scaling-up NUS requires training farmers and other stakeholders on ways to adopt adequate crop management, quality seed, select varieties, farming systems, soil management, development of new products, and market opportunities (Padulosi et al. 2013). Farmers in the Rasuwa district, in the mid-hills of Nepal, prefer to cultivate local bean, barley, millet and local maize, rather than commodity crops because they are more tolerant to water stress and extremely cold conditions (Adhikari et al. 2017). Farmers in the high-altitude, cold climate of Nepal prefer local barley with its short growing period because of a shorter growing window. Buckwheat is commonly grown in the Hindu-Kush Himalayan (HKH) region mainly because it grows fast and suppresses weeds. In Pakistan, quinoa (*Chenopodium quinoa*) grew and produced well under saline and marginal soil where other crops would not grow (Adhikari et al. 2017).

At the same time, in many parts of the HKH region, a substantial proportion of the population is facing malnutrition. Various factors are responsible for this, and lack of diversity in food and nutrition resulting from production and consumption of few crops is one of them. In the past, food baskets in this region consisted of many different edible plant species, many of which are now neglected and underutilised. This is because almost all the efforts of the Green Revolution after 1960 focused on major crops. Four crops, namely rice, wheat, maize and potato, account for about 60% of global plant-derived energy supply (Padulosi et al. 2013).

While the Green Revolution technologies substantially increased the yield of few crops and allowed countries to reduce hunger, they also resulted in inappropriate and excessive use of agrochemicals, inefficient water use, loss of beneficial biodiversity, water and soil pollution and significantly reduced crop and varietal diversity. With farming systems moving away from subsistence-based to commercial farming, farmers are also reluctant to grow these local crops because of low return, poor market value and lack of knowledge about their nutritional environmental value.

However, transition from traditional diets based on local foods to a commercial crop-based diet with high fats, salt, sugar and processed foods, increased the incidence of non-communicable diseases, such as diabetes, obesity, heart diseases and certain types of cancer (Abarca-Gómez et al. 2017; NCD-RisC 2016b, 2017b). This 'hidden hunger' – enough calories, but insufficient vitamins – is increasingly evident in mountainous communities including the HKH region.

Internationally, there is rising interest in NUS, not only because they present opportunities for fighting poverty, hunger and malnutrition, but also because of their role in mitigating climate risk in agricultural production systems. NUS play an important role in mountain agroecosystems because mountain agriculture is generally low-input agriculture, for which many NUS are well adapted.

In the HKH region, mountains are agroecologically suitable for cultivation of traditional food crops, such as barley, millet, sorghum, buckwheat, bean, grams, taro, yam and a vast range of wild fruits, vegetables and medicinal plants. In one study carried out in two villages of mid-hills in Nepal, Khanal et al. (2015) reported 52 indigenous crop species belonging to 27 families with their various uses. Farming communities continue to grow various indigenous crops, albeit in marginal land, because of their value on traditional food and associated culture. Nepal Agricultural Research Council (NARC) has identified a list of indigenous crops based on their nutritional, medicinal, cultural and other values.

Many indigenous crops supply essential micronutrients to the human body, and need to be conserved in mountain food systems. Farmers in HKH region are cultivating and maintaining various indigenous crops such as Amaranthus, barley, black gram, horse gram, yam, and sesame. because of their nutritional value. Most of these indigenous crops are comparable with commercial cereals in terms of dietary energy and protein content, but are also rich in micronutrients. For example, pearl millet has higher content of calcium, iron, zinc, riboflavin and folic acid than rice or maize (Adhikari et al. 2017).

NUS can provide both climate resilience and more options for dietary diversity to the farming communities of mountain ecosystems. Some of these indigenous crops have high medical importance. For example, mountain people in the HKH region have been using *jammun* (i.e., *Syzygium cumini*) to treat diabetes. In the Gilgit-Baltistan province of Pakistan, realising the importance of sea-buckthorn for nutritional and medicinal purposes, local communities have expanded its cultivation to larger areas. Many of these crops can be cultivated in marginal and/or fallow land which otherwise remains fallow. Most of these species are drought resistant and can be easily grown in rainfed conditions in non-irrigated land.

For example, agroforestry systems can contribute to improving food productivity while enhancing biodiversity conservation, ecological balance and restoration under changing climate conditions (Mbow et al. 2014a; Paudela et al. 2017; Newaj et al. 2016; Altieri et al. 2015). Agroforestry systems have been shown to reduce erosion through their canopy cover and their contribution to the micro-climate and erosion control (Sida et al. 2018). Adoption of conservation farming practices such as removing weeds from and dredging irrigation canals, draining and levelling land, and using organic fertilisation were among the popular conservation practices in small-scale paddy rice farming community of northern Iran (Ashoori and Sadegh 2016).

Adaptation potential of ecologically-intensive systems includes also forests and river ecosystems, where improved resource management such as soil conservation, water cycling and agrobiodiversity support the function of food production affected by severe climate change (Muthee et al. 2017). The use of non-crop plant resources in agroecosystems (permaculture, perennial polyculture) can improve ecosystem conservation and may lead to increased crop productivity (Balzan et al. 2016; Crews et al. 2018; Toensmeier 2016).

In summary, increasing the resilience of the food system through agroecology and diversification is an effective way to achieve climate change adaptation (*robust evidence, high agreement)*. Diversification in the food system is a key adaptation strategy to reduce risks (e.g., implementation of integrated production systems at landscape scales, broad-based genetic resources, and heterogeneous diets) (*medium confidence*).

5.3.2.4 Role of cultural values

Food production and consumption are strongly influenced by cultures and beliefs. Culture, values and norms are primary factors in most climate change and food system policies. The benefits of integrating cultural beliefs and ILK into formal climate change mitigation and adaptation strategies can add value to the development of sustainable climate change, rich in local aspirations, planned with, and for, local people (Nyong et al. 2007).

Cultural dimensions are important in understanding how societies establish food production systems and respond to climate change, since they help to explain differences in responses across populations to the same environmental risks (Adger et al. 2013). There is an inherent adaptability of indigenous people who are particularly connected to land use, developed for many centuries to produce specific solutions to particular climate change challenges. Acknowledging that indigenous cultures across the world are supporting many string strategies and beliefs that offer sustainable systems with pragmatic solutions will help move forward the food and climate sustainability policies. For instance, in the Sahel, the local populations have developed and implemented various adaptation strategies that sustain their resilience despite many threats (Nyong et al. 2007). There is an increased consideration of local knowledge and cultural values and norms in the design and implementation of modern mitigation and adaptation strategies.

There are some entrenched cultural beliefs and values that may be barriers to climate change adaptation. For instance, culture has been shown to be a major barrier to adaptation for the Fulbe ethnic group of Burkina Faso (Nielsen and Reenberg 2010). Thus, it is important to understand how beliefs, values, practices and habits interact with the behaviour of individuals and collectivities that have to confront climate change (Heyd and Thomas 2008). Granderson (2014) suggests that making sense of climate change and its responses at the community level demands attention to the cultural and political processes that shape how risk is conceived, prioritised and managed. For a discussion of gender issues related to climate change, see Section 5.2.

Culturally sensitive risk analysis can deliver a better understanding of what climate change means for society (O'Brien and Wolf 2010; Persson et al. 2015) and thus, how to better adapt. Murphy et al. (2016) stated that culture and beliefs play an important role in adaptive capacity but that they are not static. In the work done by Elum et al. (2017) in South Africa (about farmers' perception of climate change), they concluded that perceptions and beliefs often have negative effects on adaptation options.

Culture is a key issue in food systems and the relation of people with nature. Food is an intrinsically cultural process: food production shapes landscapes, which in turn are linked to cultural heritages and identities (Koohafkan and Altieri 2011; Fuller and Qingwen 2013), and food consumption has a strong cultural dimension. The loss of subsistence practices in modern cultures and their related ILK, has resulted in a loss of valuable adaptive capacities (Hernández-Morcillo et al. 2014). This is so because these systems are often characterised by livelihood strategies linked to the management of natural resources that have been evolved to reduce overall vulnerability to climate shocks ('adaptive strategies') and to manage their impacts ex-post ('coping strategies') (Morton 2007; López-i-Gelats et al. 2016).

5.3.3 Supply-side adaptation

Supply-side adaptation takes place in the production (of crops, livestock, and aquaculture), storage, transport, processing, and trade of food.

5.3.3.1 Crop production

There are many current agricultural management practices that can be optimised and scaled up to advance adaptation. Among the often-studied adaptation options are increased soil organic matter, improved cropland management, increased food productivity, prevention and reversal of soil erosion (see Chapter 6 for evaluation of these practices in regard to desertification and land degradation). Many analyses have demonstrated the effectiveness of soil management and changing sowing date, crop type or variety (Waongo et al. 2015; Bodin et al. 2016; Teixeira et al. 2017; Waha et al. 2013; Zimmermann et al. 2017; Chalise and Naranpanawa 2016; Moniruzzaman 2015; Sanz et al. 2017). Biophysical adaptation options also include pest and disease management (Lamichhane et al. 2015) and water management (Palmer et al. 2015; Korbeľová and Kohnová 2017).

In Africa, Scheba (2017) found that conservation agriculture techniques were embedded in an agriculture setting based on local traditional knowledge, including crop rotation, no or minimum tillage, mulching, and cover crops. Cover cropping and no-tillage also improved soil health in a highly commercialised arid irrigated system in California's San Joaquin Valley, USA (Mitchell et al. 2017). Biofertilisers can enhance rice yields (Kantachote et al. 2016), and Amanullah and Khalid (2016) found that manure and biofertiliser improve maize productivity under semi-arid conditions.

Adaptation also involves use of current genetic resources as well as breeding programmes for both crops and livestock. More drought, flood and heat-resistant crop varieties (Atlin et al. 2017; Mickelbart et al. 2015; Singh et al. 2017) and improved nutrient and water use efficiency, including overabundance as well as water quality (such as salinity) (Bond et al. 2018) are aspects to factor into the design of adaptation measures. Both availability and adoption of these varieties is a possible path for adaptation and can be facilitated by new outreach policy and capacity building.

Water management is another key area for adaptation. Increasing water availability and reliability of water for agricultural production using different techniques of water harvesting, storage, and its judicious utilisation through farm ponds, dams, and community tanks in rainfed agriculture areas have been presented by Rao et al. (2017) and Rivera-Ferre et al. (2016a). In addition, improved drainage systems (Thiel et al. 2015), and Alternate Wetting and Drying (AWD) techniques for rice cultivation (Howell et al. 2015; Rahman and Bulbul 2015) have been proposed. Efficient irrigation systems have been also analysed and proposed by Jägermeyr et al. (2016), Naresh et al. (2017), Gunarathna et al. (2017) and Chartzoulakis and Bertaki (2015). Recent innovation includes using farming systems with low usage of water such as drip-irrigation or hydroponic systems mostly in urban farming.

5.3.3.2 Livestock production systems

Considering the benefits of higher temperature in temperate climates and the increase of pasture with incremental warming in some humid and temperate grasslands, as well as potential negative effects, can be useful in planning adaptation strategies to future climate change. Rivera-Ferre et al. (2016b) characterize adaptation for different livestock systems as managerial, technical, behavioural and policy-related options. Managerial included production adjustments (e.g., intensification, integration with crops, shifting from grazing to browsing species, multispecies herds, mobility, soil and nutrient management, water management, pasture management, corralling, feed and food storage, farm diversification or cooling systems); and changes in labour allocation (diversifying livelihoods, shifting to irrigated farming, and labour flexibility). Technological options included breeding strategies and information technology research. Behavioural options are linked to cultural patterns and included encouraging social collaboration and reciprocity, for example, livestock loans, communal planning, food exchanges, and information sharing. Policy options are discussed in Section 5.7 and Chapter 7.

5.3.3.3 Aquaculture, fisheries, and agriculture interactions

Options may include livelihood diversification within and across sectors of fisheries, aquaculture and agriculture. Thus, adaptation options need to provide management approaches and policies that build the livelihood asset base, reducing vulnerability to multiple stressors with a multi-sector perspective (Badjeck et al. 2010). In Bangladesh, fishing pressure on post-larval prawns has increased as displaced farmers have shifted to fishing following salt-water intrusion of agricultural land (Ahmed et al. 2013). In West Africa, strategies to cope with sudden shifts in fisheries are wider-reaching and have included turning to seafood import (Gephart et al. 2017) or terrestrial food production, including farming and bush-meat hunting on land (Brashares et al. 2004).

Proposed actions for adaptation include effective governance, improved management and conservation, efforts to maximise societal and environmental benefits from trade, increased equitability of distribution and innovation in food production, and the continued development of low-input and low-impact aquaculture (FAO 2018c).

Particular adaptation strategies proposed by FAO (2014a) include diverse and flexible livelihood strategies, such as introduction of fish ponds in areas susceptible to intermittent flood/drought periods; flood-friendly small-scale homestead bamboo pens with trap doors allowing seasonal floods to occur without loss of stocked fish; cage fish aquaculture development using plankton feed in reservoirs created by dam building; supporting the transition to different species, polyculture and integrated systems, allowing for diversified and more resilient systems; promotion of combined rice and fish farming systems that reduce overall water needs and provide integrated pest management; and supporting transitions to alternative livelihoods.

Risk reduction initiatives include innovative weather-based insurance schemes being tested for applicability in aquaculture and fisheries and climate risk assessments introduced for integrated coastal zone management. For aquaculture's contribution to building resilient food systems, Troell et al. (2014) found that aquaculture could potentially enhance resilience through improved resource use efficiencies and increased diversification of farmed species, locales of production, and feeding strategies. Yet, its high reliance on terrestrial crops and wild fish for feeds, its dependence on freshwater and land for culture sites and its environmental impacts reduce this potential. For instance, the increase in aquaculture worldwide may enhance land competition for feed crops, increasing price levels and volatility and worsening food insecurity among the most vulnerable populations.

5.3.3.4 Transport and storage

Fewer studies have been done on adaptation of food system transport and storage compared to the many studies on adaptation to climate in food production.

Transport. One transport example is found in Bangkok. Between mid-November 2011 and early January 2012, Bangkok, the capital city of Thailand, faced its most dramatic flood in approximately 70 years with most transport networks cut-off or destroyed. This caused large-scale disruption of the national food supply chains since they were centrally organised in the capital city (Allen et al. 2017). From this experience, the construction and management of 'climate-proof' rural roads and transport networks is argued as one the most important adaptation strategies for climate change and food security in Thailand (Rattanachot et al. 2015).

Similarly in Africa, it has been shown that enhanced transportation networks combined with other measures could reduce the impact of climate change on food and nutrition security (Brown et al. 2017b). This suggests that strengthening infrastructure and logistics for transport would significantly enhance resilience to climate change, while improving food and nutrition security in developing counties.

Storage. Storage refers to both structures and technologies for storing seed as well as produce. Predominant storage methods used in Uganda are single-layer woven polypropylene bags (popularly called 'kavera' locally), chemical insecticides and granaries. Evidence from Omotilewa et al. (2018) showed that the introduction of new storage technology called Purdue Improved Crop Storage (PICS) could contribute to climate change adaptation. PICS is a chemical-free airtight triple-layered technology consisting of two high-density polyethylene inner liners and one outer layer of woven polypropylene bag. Its adoption has increased the number of households planting hybrid maize varieties that are more susceptible to insect pests in storage than traditional lower-yielding varieties. Such innovations could help to protect crops more safely and for longer periods from postharvest insect pests that are projected to increase as result of climate change, thus contributing to food security.

In the Indo-Gangetic Plain many different storage structures based on ILK provide reliable and low-cost options made of local materials. For example, elevated grain stores protectharvested cereals from floods, but also provide for air circulation to prevent rot and to control insects and other vermin (Rivera-Ferre et al. 2013).

5.3.3.5 Trade and processing

Adaptation measures are also being considered in trade, processing and packaging, other important components of the food system. These will enable availability, stability, and safety of food under changing climate conditions.

Trade. Brooks and Matthews (2015) found that food trade increases the availability of food by enabling products to flow from surplus to deficit areas, raises incomes and favours access to food, improves utilisation by increasing the diversity of national diets while pooling production risks across individual markets to maintain stability.

Processing. Growth of spoilage bacteria of red meat and poultry during storage due to increasing temperature has been demonstrated by European Food Safety Authority (EFSA Panel on Biological Hazards 2016). In a recent experiment conducted on the optimisation of processing conditions of Chinese traditional smoke-cured bacon, Larou, Liu et al. (2018a) showed that the use of a new natural coating solution composed of lysozyme, sodium alginate, and chitosan during the storage period resulted in 99.69% rate of reducing deterioration after 30-day storage. Also, the use of High Hydrostatic Pressure (HHP) technology to inactivate pathogenic, spoilage microorganisms and enzymes (with little or no effects on the nutritional and sensory quality of foods) have been described by Wang et al. (2016) and Ali et al. (2018) as new advances in processing and packaging fruits, vegetables, meats, seafood, dairy, and egg products.

In summary, there are many practices that can be optimised and scaled up to advance supply-side adaptation. On-farm adaptation options include increased soil organic matter and erosion control in cropland, improved livestock and grazing land management, and transition to different species, polyculture and integrated systems in aquaculture. Crop and livestock genetic improvements include tolerance to heat, drought, and pests and diseases. Food transport, storage, trade, and processing will likely play increasingly important roles in adapting to climate change-induced food insecurity.

5.3.4 Demand-side adaptation

Adaptation in the demand side of the food system involves consumption practices, diets, and reducing food loss and waste. Recent studies showed that supply-side adaptation measures alone will not be sufficient to sustainably achieve food security under climate change (Springmann et al. 2018b; Swinburn et al. 2019; Bajželj et al. 2014). As noted by Godfray (2015), people with higher income demand more varied diets, and typically ones that are richer in meat and other food types that require more resources to produce. Therefore, both supply-side (production, processing, transport, and trade) and demand-side solutions (for example, changing diets, food loss and waste reduction) can be effective in adapting to climate change (Creutzig et al. 2016) (see Section 5.5.2.5 for food loss and waste).

The implications of dietary choice can have severe consequences for land. For example, Alexander et al. (2016), found that if every country were to adopt the UK's 2011 average diet and meat consumption, 95% of global habitable land area would be needed for agriculture – up from 50% of land currently used. For the average USA diet, 178% of global land would be needed (relative to 2011) (Alexander et al. 2016); and for 'business as usual' dietary trends and existing rates of improvement in yields, 55% more land would be needed above baseline (2009) (Bajželj et al. 2014). Changing dietary habits have been suggested as an effective food route to affect land use (Beheshti et al. 2017) and promote adaptation to climate change through food demand.

Most literature has focused on demand-side options that analyse the effects on climate change mitigation by dietary changes. Little focus has been brought on demand-side adaptation measures to adjust the demand to the food challenges related to drivers such as market, climate change, inputs limitations (for example, fossil fuels, nitrogen, phosphorus), food access, and quality. Adding to that, the high cost of nutritious foods contributes to a higher risk of overweight and obesity (FAO 2018d). Adaptation measures relate also to the implications of easy access to inexpensive, high-calorie, low-nutrition foods which have been shown to lead to malnutrition (Section 5.1). Therefore, adaptation related to diet may be weighed against the negative side effects on health of current food choices.

Reduction in the demand for animal-based food products and increasing proportions of plant-based foods in diets, particularly pulses and nuts; and replacing red meat with other more efficient protein sources are demand-side adaptation measures (Machovina et al. 2015) (Section 5.5.2). For example, replacing beef in the USA diet with poultry can meet caloric and protein demands of about 120 to 140 million additional people consuming the average American diet (Shepon et al. 2016). Similar suggestions are made for adopting the benefits of moving to plant-based protein, such as beans (Harwatt et al. 2017).

The main reason why reducing meat consumption is an adaptation measure is because it reduces pressure on land and water and thus our vulnerability to climate change and inputs limitations (Vanham et al. 2013). For animal feed, ruminants can have positive ecological effects (species diversity, soil carbon) if they are fed extensively on existing grasslands. Similarly, reducing waste at all points along the entire food chain is a significant opportunity for improving demand-side adaptation measures (Godfray 2015).

It is important to highlight the opportunities for improving the feed-to-meat conversion considered as a form of food loss. However, the unique capacity of ruminants to produce high-quality food from low-quality forage, in particular from landscapes that cannot be cropped and from cellulosic biomass that humans cannot digest could be seen as an effective way to improve the feed:meat ratio (Cawthorn and Hoffman 2015).

In summary, there is potential for demand-side adaptation, such as adoption of diets low in animal-sourced products, in conjunction with reduction in food loss and waste to contribute to reduction in food demand, land sparing, and thus need for adaptation.

5.3.5 Institutional measures

To facilitate the scaling up of adaptation throughout the food system, institutional measures are needed at global, regional, national, and local levels (Section 5.7). Institutional aspects, including policies and laws, depend on scale and context. International institutions (financial and policies) are driving many aspects of global food systems (for example, UN agencies, international private sector agribusinesses and retailers). Many others operate at local level and strongly influence livelihoods and markets of smallholder farmers. Hence, differentiation in the roles of the organisations, their missions and outcomes related to food and climate change action need to be clearly mapped and understood.

Awareness about the institutional context within which adaptation planning decisions are made is essential for the usability of climate change projection (Lorenz 2017) (Chapter 7). In the planning and operational process of food production, handling and consumption, the environment benefits and climate change goals can be mainstreamed under sustainable management approaches that favour alternative solutions for inputs, energy consumption, transformation and diet. For instance, land-use planning would guide current and future decision-making and planners in exploring uncertainty to increase the resilience of communities (Berke and Stevens 2016). One of the important policy implications for enhanced food security are the trade-offs between agricultural production and environmental concerns, including the asserted need for global land-use expansion, biodiversity and ecological restoration (Meyfroidt 2017) (Section 5.6).

There are a number of adaptation options in agriculture in the form of policy, planning, governance and institutions (Lorenz 2017). For example, early spatial planning action is crucial to guide decision-making processes and foster resilience in highly uncertain future climate change (Brunner and Grêt-Regamey, 2016). Institutions may develop new capacities to empower value chain actors, take climate change into account as they develop quality products, promote adoption of improved diet for healthier lifestyles, aid the improvement of livelihoods of communities, and further socioeconomic development (Sehmi et al. 2016). Other adaptation policies include property rights and land tenure security as legal and institutional reforms to ensure transparency and access to land that could stimulate adaptation to climate change (Antwi-Agyei et al. 2015).

5.3.5.1 Global initiatives

Climate change poses serious wide-ranging risks, requiring a broader approach in fighting the phenomenon. The United Nations Framework Convention on Climate Change (UNFCCC) and its annual Conferences of the Parties (COPs) has been instrumental in ensuring international cooperation in the field of tackling the impacts of climate change in a broader framework (Clémençon 2016). The National Adaptation Plan (NAP) programme under the UNFCCC was established to: identify vulnerable regions; assess the impacts of climate change on food security; and prioritise adaptation measures for implementation to increase resilience. The National Adaptation Programs of Action (NAPAs) was also established to support least-developed countries (LDCs) in addressing their particular challenges in adaptation, to enhance food security among other priorities.

The Paris Agreement (UNFCCC 2015) is a major victory for small island states and vulnerable nations that face climate change-related impacts of floods and droughts resulting in food security challenges. Adaptation and mitigation targets set by the parties through their nationally determined commitments (NDCs) are reviewed internationally to ensure consistency and progress towards actions (Falkner 2016).

The Food and Agriculture Organization of the United Nations (FAO) also plays a significant role in designing and coordinating national policies to increase adaptation and food security. The five key strategic objectives of FAO (help eliminate hunger, food insecurity and malnutrition; make agriculture, forestry and fisheries more productive and sustainable; reduce rural poverty; enable inclusive and efficient agricultural and food systems; and increase the resilience of livelihoods to climate threats) (FAO 2018e), all relate to building resilience and increasing global adaptation to climate variability.

In support of the Paris Agreement, FAO launched a global policy, 'Tracking Adaptation' with the aim of monitoring the adaptation processes and outcomes of the parties to increase food security and of making available technical information for evaluation by stakeholders. In response to the estimated world population of 9.7 billion by 2050, FAO adopted the Climate Smart Agriculture (CSA) approach to increase global food security without compromising environmental quality (Section 5.6). FAO supports governments at the national level to plan CSA programmes and to seek climate finance to fund their adaptation programmes.

The Global Commission on Adaptation, co-managed by World Resources Institute (WRI) and the Global Center on Adaptation, seeks to accelerate adaptation action by elevating the political visibility of adaptation and focusing on concrete solutions (Global Commission on Adaptation 2019). The Commission works to demonstrate that adaptation is a cornerstone of better development, and can help improve lives, reduce poverty, protect the environment, and enhance resilience around the world. The Commission is led by Ban Ki-moon, 8th Secretary-General of the United Nations, Bill Gates, co-chair of the Bill & Melinda Gates Foundation, and Kristalina Georgieva, CEO, World Bank. It is convened by 17 countries and guided by 28 commissioners. A global network of research partners and advisors provide scientific, economic, and policy analysis.

5.3.5.2 National policies

The successful development of food systems under climate change conditions requires a national-level management that involves the cooperation of a number of institutions and governance entities to enable more sustainable and beneficial production and consumption practices.

For example, Nepal has developed a novel multi-level institutional partnership, under the Local Adaptation Plan of Action (LAPA), which is an institutional innovation that aims to better integrate local adaptation planning processes and institutions into national adaptation processes. That includes collaboration with farmers and other non-governmental organisations (Chhetri et al. 2012). By combining conventional technological innovation process with the tacit knowledge of farmers, this new alliance has been instrumental in the innovation of location-specific technologies thereby facilitating the adoption of technologies in a more efficient manner.

National Adaptation Planning of Indonesia was officially launched in 2014 and was an important basis for ministries and local governments to mainstream climate change adaptation into their respective sectoral and local development plans (Kawanishi et al. 2016). Crop land-use policy – to switch from crops that are highly impacted by climate change to those that are less vulnerable – were suggested for improving climate change adaptation policy processes and outcomes in Nepal (Chalise and Naranpanawa 2016).

Enhancement of representation, democratic and inclusive governance, as well as equity and fairness for improving climate change adaptation policy processes and outcomes in Nepal were also suggested as institutional measures by Ojha et al. (2015). Further, food, nutrition, and health policy adaptation options such as social safety nets and social protection have been implemented in India, Pakistan, Middle East and North Africa (Devereux 2015; Mumtaz and Whiteford 2017; Narayanan and Gerber 2017).

Financial incentives policies at the national scale used as adaptation options include taxes and subsidies; index-based weather insurance schemes; and catastrophe bonds (Zilberman et al. 2018; Linnerooth-Bayer and Hochrainer-Stigler 2015; Ruiter et al. 2017 and Campillo et al. 2017). Microfinance, disaster contingency funds, and cash transfers are other mechanisms (Ozaki 2016 and Kabir et al. 2016).

5.3.5.3 Community-based adaptation

Community-based adaptation (CBA) builds on social organisational capacities and resources to address food security and climate change. CBA represents bottom-up approaches and localised adaptation measures where social dynamics serve as the power to respond to the impacts of climate change (Ayers and Forsyth 2009). It identifies, assists, and implements development activities that strengthen the capacity of local people to adapt to living in a riskier and less predictable climate, while ensuring their food security.

Klenk et al. (2017) found that mobilisation of local knowledge can inform adaptation decision-making and may facilitate greater flexibility in government-funded research. As an example, rural innovation in terrace agriculture developed on the basis of a local coping mechanism and adopted by peasant farmers in Latin America may serve as an adaptation option to climate change (Bocco and Napoletano, 2017). Clemens et al. (2015) indicated that learning alliances provided social learning and knowledge-sharing in Vietnam through an open dialogue platform that provided incentives and horizontal exchange of ideas.

Community-based adaptation generates strategies through participatory processes, involving local stakeholders and development and disaster risk reduction practitioners. Fostering collaboration and community stewardship is central to the success of CBA (Scott et al. 2017). Preparedness behaviours that are encouraged include social connectedness, education, training, and messaging; CBA also can encompass beliefs that might improve household preparedness to climate disaster risk (Thomas et al. 2015). Reliance on social networks, social groups connectivities, or moral economies reflect the importance of collaboration within communities (Reuter 2018; Schramski et al. 2017).

Yet, community-based adaptation also needs to consider methods that engage with the drivers of vulnerability as part of community-based approaches, particularly questions of power, culture, identity and practice (Ensor et al. 2018). The goal is to avoid maladaptation or exacerbation of existing inequalities within the communities (Buggy and McNamara 2016). For example, in the Pacific Islands, elements considered in a CBA plan included people's development aspirations; immediate economic, social and environmental benefits; dynamics of village governance, social rules and protocols; and traditional forms of knowledge that could inform sustainable solutions (Remling and Veitayaki 2016).

With these considerations, community-based adaptation can help to link local adaptation with international development and climate change policies (Forsyth 2013). In developing CBA programmes, barriers exist that may hinder implementation. These include poor coordination within and between organisations implementing adaptation options, poor skills, poor knowledge about climate change, and inadequate communication among stakeholders (Spires et al. 2014). A rights-based approach has been suggested to address issues of equality, transparency, accountability and empowerment in adaptation to climate change (Ensor et al. 2015).

In summary, institutional measures, including risk management, policies, and planning at global, national, and local scales can support adaptation. Advance planning and focus on institutions can aid in guiding decision-making processes and foster resilience. There is evidence that institutional measures can support the scaling up of adaptation and thus there is reason to believe that systemic resilience is achievable.

5.3.6 Tools and finance

5.3.6.1 Early warning systems

Many countries and regions in the world have adopted early warning systems (EWS) to cope with climate variability and change as it helps to reduce interruptions and improve response times before and after extreme weather events (Ibrahim and Kruczkiewicz 2016). The Early Warning and Early Action (EW/EA) framework has been implemented in West Africa (Red Cross 2011) and Mozambique (DKNC 2012). Bangladesh has constructed cyclone shelters where cyclone warnings are disseminated and responses organised (Mallick et al. 2013). In Benin, a Standard Operating Procedure is used to issue early warnings through the UNDP Climate Information and Early Warning Systems Project (UNDP 2016).

However, there are some barriers to building effective early warning systems in Africa, such as lack of reliable data and distribution systems, lack of credibility, and limited relationships with media and government agencies (UNDP 2016). Mainstreaming early warning systems in adaptation planning could present a significant opportunity for climate disaster risk reduction (Zia and Wagner 2015). Enenkel et al. (2015) suggested that the use of smartphone applications that concentrate on food and nutrition security could help with more frequent and effective monitoring of food prices, availability of fertilisers and drought-resistant seeds, and could help to turn data streams into useful information for decision support and resilience building.

GIS and remote sensing technology are used for monitoring and risk quantification for broad-spectrum stresses such as drought, heat, cold, salinity, flooding, and pests (Skakun et al. 2017; Senay et al. 2015; Hossain et al. 2015 and; Brown 2016), while site-specific applications, such as drones, for nutrient management, precision fertilisers, and residue management can help devise context-specific adaptations (Campbell et al. 2016 and; Baker et al. 2016). Systematic monitoring and remote sensing options, as argued by Aghakouchak et al. (2015), showed that satellite observations provide opportunities to improve early drought warning. Waldner et al. (2015) found that cropland mapping allows strategic food and nutrition security monitoring and climate modelling.

Access to a wide range of adaptation technologies for precipitation change is important, such as rainwater harvesting, wastewater treatment, stormwater management and bioswales, water demand reduction, water-use efficiency, water recycling and reuse, aquifer recharge, inter-basin water transfer, desalination, and surface-water storage (ADB 2014).

5.3.6.2 Financial resources

Financial instruments such as micro-insurance, index-based insurance, provision of post-disaster finances for recovery and pre-disaster payment are fundamental means to reduce lower and medium level risks (Linnerooth-Bayer and Hochrainer-Stigler 2014). Fenton & Paavola, 2015; Dowla, 2018). Hammill et al. (2010) found that microfinance services (MFS) are especially helpful for the poor. MFS can provide poor people with the means to diversify, accumulate and manage the assets needed to become less susceptible to shocks and stresses. As a result, MFS plays an important role in vulnerability reduction and climate change adaptation among some of the poor. The provision of small-scale financial products to low-income and otherwise disadvantaged groups by financial institutions can serve as adaptation to climate change. Access to finance in the context of climate change adaptation that focuses on poor households and women in particular is bringing encouraging results (Agrawala and Carraro 2010).

In summary, effective adaptation strategies can reduce the negative impacts of climate change. Food security under changing climate conditions depends on adaptation throughout the entire food system – production, supply chain, and consumption/demand, as well as reduction of food loss and waste. Adaptation can be autonomous, incremental, or transformative, and can reduce vulnerability and enhance resilience. Local food systems are embedded in culture, beliefs and values, and ILK can contribute to enhancing food system resilience to climate change (*high confidence*). Institutional and capacity-building measures are needed to scale up adaptation measures across local, national, regional, and global scales.

5.4 Impacts of food systems on climate change

5.4.1 Greenhouse gas emissions from food systems

This chapter assesses the contributions of the entire food system to greenhouse gas (GHG) emissions. Food systems emissions include CO_2 and non-CO_2 gases, specifically those generated from: (i) crop and livestock activities within the farm gate (Table 5.4, category 'Agriculture'); (ii) land use and land-use change dynamics associated with agriculture (Table 5.4, category 'Land Use'); and (iii) food processing, retail and consumption patterns, including upstream and downstream processes such as manufacture of chemical fertilisers

Table 5.4 | **GHG emissions ($GtCO_2$-eq yr^{-1}) from the food system and their contribution (%) to total anthropogenic emissions. Mean of 2007–2016 period.**

Food system component	Emissions (Gt CO_2eq yr^{-1})	Share in mean total emissions (%)
Agriculture	6.2 ± 1.4[a,b]	9–14%
Land use	4.9 ± 2.5[a]	5–14%
Beyond farm gate	2.6[c] – 5.2[d]	5–10%[e]
Food system (total)	10.8 – 19.1	21–37%

Notes: Food system emissions are estimated from a) FAOSTAT (2018), b) US EPA (2012), c) Poore and Nemecek (2018) and d) Fischedick et al. (2014) (using square root of sum of squares of standard deviations when adding uncertainty ranges; see also Chapter 2); e) rounded to nearest fifth percentile due to assessed uncertainty in estimates. Percentage shares were computed by using a total emissions value for the period 2007–2016 of nearly 52 $GtCO_2$-eq yr^{-1} (Chapter 2), using GWP values of the IPCC AR5 with no climate feedback (GWP-CH_4=28; GWP-N_2O=265).

and fuel (Table 5.4, category 'Beyond Farm Gate'). The first two categories comprise emissions reported by countries in the AFOLU (agriculture, forestry, and other land use) sectors of national GHG inventories; the latter comprises emissions reported in other sectors of the inventory, as appropriate. For instance, industrial processes, energy use, and food loss and waste.

The first two components (agriculture and land use) identified above are well quantified and supported by an ample body of literature (Smith et al. 2014). During the period 2007–2016, global agricultural non-CO_2 emissions from crop and livestock activities within the farm gate were 6.2 ± 1.4 $GtCO_2$-eq yr^{-1} during 2007–2016, with methane (142 ± 42 $MtCH_4$ yr^{-1}, or 4.0 ± 1.2 $GtCO_2$-eq yr^{-1}) contributing in CO_2-eq about twice as much as nitrous oxide (8.3 ± 2.5 MtN_2O yr^{-1}, or 2.2 ± 0.7 $GtCO_2$-eq yr^{-1}) to this total (Table 2.2 in Chapter 2). Emissions from land use associated with agriculture in some regions, such as from deforestation and peatland degradation (both processes involved in preparing land for agricultural use), added another 4.9 ± 2.5 $GtCO_2$-eq yr^{-1} (Chapter 2) globally during the same period. These estimates are associated with uncertainties of about 30% (agriculture) and 50% (land use), as per IPCC AR5 (Smith et al. 2014).

Agriculture activities within the farm gate and associated land-use dynamics are therefore responsible for about 11.1 ± 2.9 $GtCO_2$-eq yr^{-1}, or some 20% of total anthropogenic emissions (Table 5.4), consistent with post-AR5 findings (for example, Tubiello et al. 2015). In terms of individual gases, the contributions of agriculture to total emissions by gas are significantly larger. For instance, over the period 2010–2016, methane gas emissions within the farm gate represented about half of the total CH_4 emitted by all sectors, while nitrous dioxide gas emissions within the farm gate represented about three-quarters of the total N_2O emitted by all sectors (Tubiello 2019). In terms of carbon, CO_2 emissions from deforestation and peatland degradation linked to agriculture contributed about 10% of the CO_2 emitted by all sectors in 2017 (Le Quéré et al. 2018).

Food systems emissions beyond the farm gate, such as those upstream from manufacturing of fertilisers, or downstream such as food processing, transport and retail, and food consumption, generally add to emissions from agriculture and land use, but their estimation is very uncertain due to lack of sufficient studies. The IPCC AR5 (Fischedick et al. 2014) provided some information on these other food system components, noting that emissions beyond the farm gate in developed countries may equal those within the farm gate, and cited one study estimating world total food system emissions to be up to 30% of total anthropogenic emissions (Garnett 2011). More recently, Poore and Nemecek (2018), by looking at a database of farms and using a combination of modelling approaches across relevant processes, estimated a total contribution of food systems around 26% of total anthropogenic emissions. Total emissions from food systems may account for 21–37% of total GHG emissions (*medium confidence*).

Based on the available literature, a break-down of individual contributions of food systems emissions is show in Table 5.4, between those from agriculture within the farm gate (9–14%) (*high confidence*); emissions from land use and land-use change dynamics such as deforestation and peatland degradation, which are associated with agriculture in many regions (5–14%) (*high confidence*); and those from food supply chain activities past the farm gate, such as storage, processing, transport, and retail (5–10%) *(limited evidence, medium agreement)*. Note that the corresponding lower range of emissions past the farm gate, for example, 2.6 $GtCO_2$-eq yr^{-1} (Table 5.4), is consistent with recent estimates made by Poore and Nemecek (2018). Contributions from food loss and waste are implicitly included in these estimates of total emissions from food systems (Section 5.5.2.5). They may account for 8–10% of total anthropogenic GHG emissions (*low confidence*) (FAO 2013b).

5.4.2 Greenhouse gas emissions from croplands and soils

Since AR5, a few studies have quantified separate contributions of crops and soils on the one hand, and livestock on the other, to the total emissions from agriculture and associated land use. For instance, Carlson et al. (2017) estimated emissions from cropland to be in the range of 2–3 $GtCO_2$-eq yr^{-1}, including methane emissions from rice, CO_2 emissions from peatland cultivation, and N_2O emissions from fertiliser applications. Data from FAOSTAT (2018), recomputed to use AR5 GWP values, indicated that cropland emissions from these categories were 3.6 ± 1.2 $GtCO_2$-eq yr^{-1} over the period 2010–2016. Two-thirds of this were related to peatland degradation, followed by N_2O emissions from synthetic fertilisers and methane emissions from paddy rice fields (Tubiello 2019). These figures are a subset of the total emissions from agriculture and land use reported in Table 5.4. Asia, especially India, China and Indonesia accounted for roughly 50% of global emissions from croplands. Figure 5.9 shows the spatial distribution of emissions from cropland according to Carlson et al. (2017), not including emissions related to deforestation or changes in soil carbon.

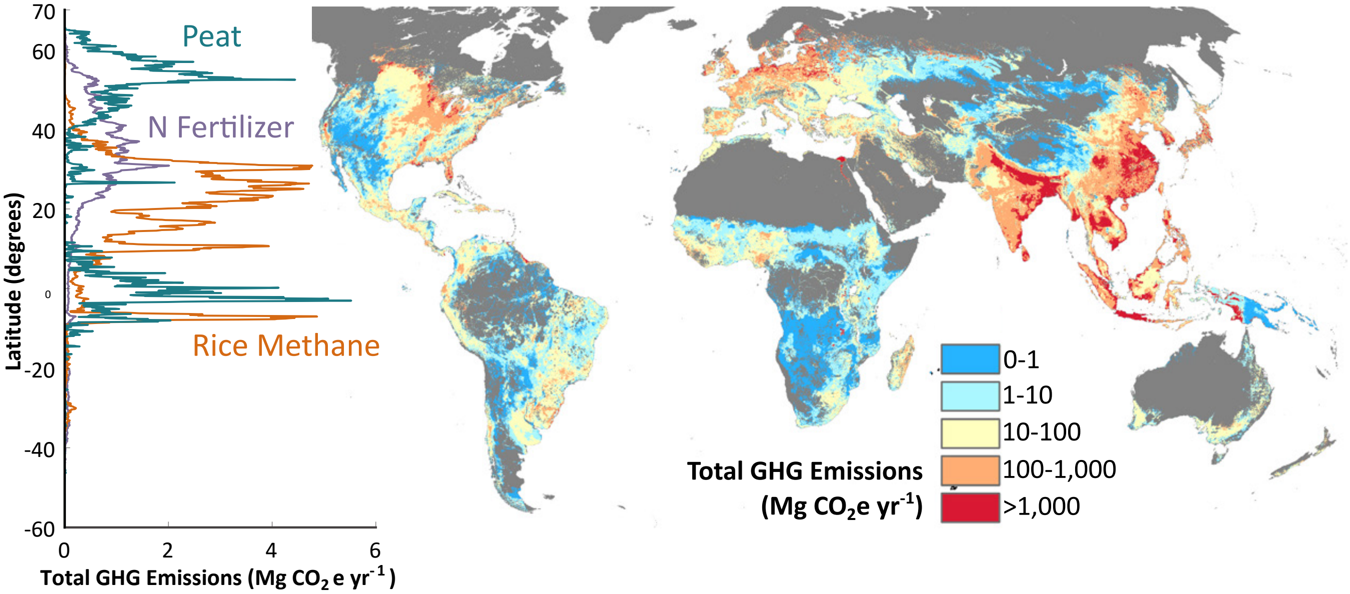

Figure 5.9 | Cropland GHGs consist of CH_4 from rice cultivation, CO_2, N_2O, and CH_4 from peatland draining, and N_2O from N fertiliser application. Total emissions from each grid cell are concentrated in Asia, and are distinct from patterns of production intensity (Carlson et al. 2017).

5.4.3 Greenhouse gas emissions from livestock

Emissions from livestock include non-CO_2 gases from enteric fermentation from ruminant animals and from anaerobic fermentation in manure management processes, as well as non-CO_2 gases from manure deposited on pastures (Smith et al. 2014). Estimates after the AR5 include those from Herrero et al. (2016), who quantified non-CO_2 emissions from livestock to be in the range of 2.0–3.6 $GtCO_2$-eq yr^{-1}, with enteric fermentation from ruminants being the main contributor. FAOSTAT (2018) estimates of these emissions, renormalized to AR5 GWP values, were 4.1 ± 1.2 $GtCO_2$-eq yr^{-1} over the period 2010–2016.

These estimates of livestock emissions are for those generated within the farm gate. Adding emissions from relevant land-use change, energy use, and transportation processes, FAO (2014a) and Gerber et al. (2013) estimated livestock emissions of up to 5.3 ±1.6 $GtCO_2$-eq yr^{-1} circa the year 2010. This data came from original papers, but was scaled to SAR global warming potential (GWP) values for methane, for comparability with previous results.

All estimates agree that cattle are the main source of global livestock emissions (65–77%). Livestock in low and middle-income countries contribute 70% of the emissions from ruminants and 53% from monogastric livestock (animals without ruminant digestion processes such as pigs and poultry), and these are expected to increase as demand for livestock products increases in these countries (Figure 5.10). In contrast to the increasing trend in absolute GHG emissions, GHG emissions intensities, defined as GHG emissions per unit produced, have declined globally and are about 60% lower today than in the 1960s. This is largely due to improved meat and milk productivity of cattle breeds (FAOSTAT 2018; Davis et al. 2015).

Still, products like red meat remain the most inefficient in terms of emissions per kg of protein produced in comparison to milk, pork, eggs and all crop products (IPCC 2014b). Yet, the functional unit used in these measurements is highly relevant and may produce different results (Salou et al. 2017). For instance, metrics based on products tend to rate intensive livestock systems as efficient, while metrics based on area or resources used tend to rate extensive systems as efficient (Garnett 2011). In ruminant dairy systems, less intensified farms show higher emissions if expressed by product, and lower emissions if expressed by Utilizable Agricultural Land (Gutiérrez-Peña et al. 2019; Salvador et al. 2017; Salou et al. 2017).

Furthermore, if other variables are used in the analysis of GHG emissions of different ruminant production systems, such as human-edible grains used to feed animals instead of crop waste and pastures of marginal lands, or carbon sequestration in pasture systems in degraded lands, then the GHG emissions of extensive systems are reduced. Reductions of 26% and 43% have been shown in small ruminants, such as sheep and goats (Gutiérrez-Peña et al. 2019; Salvador et al. 2017; Batalla et al. 2015 and Petersen et al. 2013). In this regard, depending on what the main challenge is in different regions (for example, undernourishment, over-consumption, natural resources degradation), different metrics could be used as reference. Other metrics that consider nutrient density have been proposed because they provide potential for addressing both mitigation and health targets (Doran-Browne et al. 2015).

Uncertainty in worldwide livestock population numbers remains the main source of variation in total emissions of the livestock sector, while at the animal level, feed intake, diet regime, and nutritional composition are the main sources of variation through their impacts on enteric fermentation and manure N excretion.

Increases in economies of scale linked to increased efficiencies and decreased emission intensities may lead to more emissions, rather than less, an observed dynamic referred to by economists as a 'rebound effect'. This is because increased efficiency allows

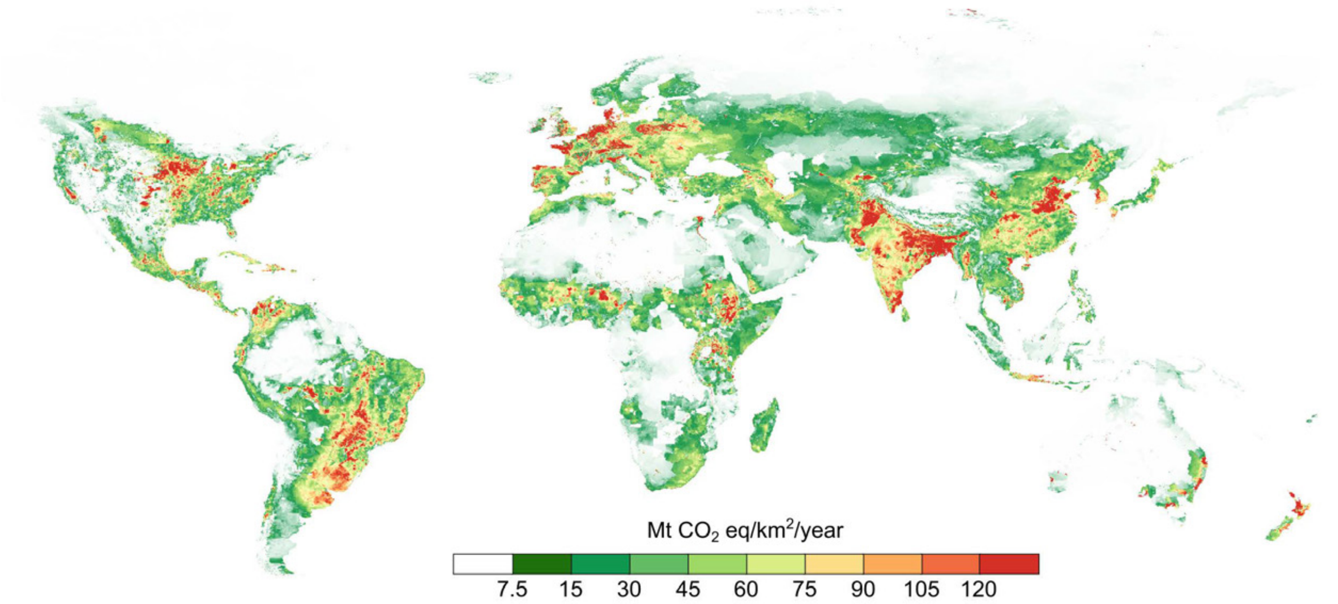

Figure 5.10 | Global GHG emissions from livestock for 1995–2005 (adapted from Herrero et al. 2016a).

production processes to be performed using fewer resources and often at lower cost. This in turn influences consumer behaviour and product use, increasing demand and leading to increased production. In this way, the expected gains from new technologies that increase the efficiency of resource use may be reduced (for example, increase in the total production of livestock despite increased efficiency of production due to increased demand for meat sold at lower prices). Thus, in order for the livestock sector to provide a contribution to GHG mitigation, reduction in emissions intensities need to be accompanied by appropriate governance and incentive mechanisms to avoid rebound effects, such as limits on total production.

Variation in estimates of N_2O emissions are due to differing (i) climate regimes, (ii) soil types, and (iii) N transformation pathways (Charles et al. 2017 and Fitton et al. 2017). It was recently suggested that N_2O soil emissions linked to livestock through manure applications could be 20–40% lower than previously estimated in some regions. For instance, in Sub-Saharan Africa and Eastern Europe (Gerber et al. 2016) and from smallholder systems in East Africa (Pelster et al. 2017). Herrero et al. (2016a) estimated global livestock enteric methane to range from 1.6–2.7 Gt CO_2-eq, depending on assumptions of body weight and animal diet.

5.4.4 Greenhouse gas emissions from aquaculture

Emissions from aquaculture and fisheries may represent some 10% of total agriculture emissions, or about 0.58 $GtCO_2$-eq yr^{-1} (Barange et al. 2018), with two-thirds being non-CO_2 emissions from aquaculture (Hu et al. 2013; Yang et al. 2015) and the rest due to fuel use in fishing vessels. They were not included in Table 5.4 under agriculture emissions, as these estimates are not included in national GHG inventories and global numbers are small as well as uncertain.

Methodologies to measure aquaculture emissions are still being developed (Vasanth et al. 2016). N_2O emissions from aquaculture are partly linked to fertiliser use for feed as well as aquatic plant growth, and depend on the temperature of water as well as on fish production (Paudel et al. 2015). Hu et al. (2012) estimated the global N_2O emissions from aquaculture in 2009 to be 0.028 $GtCO_2$-eq yr^{-1}, but could increase to 0.114 $GtCO_2$-eq yr^{-1} (that is 5.72% of anthropogenic N_2O–N emissions) by 2030 for an estimated 7.10% annual growth rate of the aquaculture industry. Numbers estimated by Williams and Crutzen (2010) were around 0.036 $GtCO_2$-eq yr^{-1}, and suggested that this may rise to more than 0.179 $GtCO_2$-eq yr^{-1} within 20 years for an estimated annual growth of 8.7%. Barange et al. (2018) assessed the contribution of aquaculture to climate change as 0.38 $GtCO_2$-eq yr^{-1} in 2010, around 7% of those from agriculture.

CO_2 emissions coming from the processing and transport of feed for fish raised in aquaculture, and also the emissions associated with the manufacturing of floating cultivation devices (e.g., rafts or floating fish-farms), connecting or mooring devices, artificial fishing banks or reefs, and feeding devices (as well as their energy consumption) may be considered within the emissions from the food system. Indeed, most of the GHG emissions from aquaculture are associated with the production of raw feed materials and secondarily, with the transport of raw materials to mills and finished feed to farms (Barange et al. 2018).

5.4.5 Greenhouse gas emissions from inputs, processing, storage and transport

Apart from emissions from agricultural activities within the farm gate, food systems also generate emissions from the pre- and post-production stages in the form of input manufacturing (fertilisers, pesticides, feed production) and processing, storage, refrigeration, retail, waste disposal, food service, and transport. The total contribution of these combined activities outside the farm gate is not well documented. Based on information reported in the AR5 (Fischedick et al. 2014), we estimated their total contribution to be roughly 10% of total anthropogenic emissions (Table 5.4). There is no post-AR5 assessment at the global level in terms of absolute emissions. Rather, several studies have recently investigated how the combined emissions within and outside the farm gate are embedded in food products and thus associated with specific dietary choices (see next section). Below important components of food systems emissions beyond the farm gate are discussed based on recent literature.

Refrigerated trucks, trailers, shipping containers, warehouses, and retail displays that are vital parts of food supply chains all require energy and are direct sources of GHG emissions. Upstream emissions in terms of feed and fertiliser manufacture and downstream emissions (transport, refrigeration) in intensive livestock production (dairy, beef, pork) can account for up to 24–32% of total livestock emissions, with the higher fractions corresponding to commodities produced by monogastric animals (Weiss and Leip 2012). The proportion of upstream/downstream emissions fall significantly for less-intensive and more-localised production systems (Mottet et al. 2017a).

Transport and processing. Recent globalisation of agriculture has promoted industrial agriculture and encouraged value-added processing and more distant transport of agricultural commodities, all leading to increased GHG emissions. Although often GHG-intensive, food transportation plays an important role in food chains: it delivers food from producers to consumers at various distances, particularly to feed people in food-shortage zones from food-surplus zones. (Section 5.5.2.6 for assessment of local food production.)

To some extent, processing is necessary in order to make food supplies more stable, safe, long-lived, and in some cases, nutritious (FAO 2007). Agricultural production within the farm gate may contribute 80–86% of total food-related emissions in many countries, with emissions from other processes such as processing and transport being small (Vermeulen et al. 2012). However, in net food-importing countries where consumption of processed food is common, emissions from other parts of the food lifecycle generated in other locations are much higher (Green et al. 2015).

A study conducted by Wakeland et al. (2012) in the USA found that the transportation-related carbon footprint varies from a few percent to more than half of the total carbon footprint associated with food production, distribution, and storage. Most of the GHGs emitted from food processing are a result of the use of electricity, natural gas, coal, diesel, gasoline or other energy sources. Cookers, boilers, and furnaces emit carbon dioxide, and wastewater emits methane and nitrous oxide. The most energy-intensive processing is wet milling of maize, which requires 15% of total USA food industry energy (Bernstein et al. 2008); processing of sugar and oils also requires large amounts of energy.

5.4.6 Greenhouse gas emissions associated with different diets

There is now extensive literature on the relationship between food products and emissions, although the focus of the studies has been on high-income countries. Godfray et al. (2018) updated Nelson et al. (2016), a previous systematic review of the literature on environmental impacts associated with food, and concluded that higher consumption of animal-based foods was associated with higher estimated environmental impacts, whereas increased consumption of plant-based foods was associated with estimated lower environmental impact. Assessment of individual foods within these broader categories showed that meat – sometimes specified as ruminant meat (mainly beef) – was consistently identified as the single food with the greatest impact on the environment, most often in terms of GHG emissions and/or land use per unit commodity. Similar hierarchies, linked to well-known energy losses along trophic chains, from roots to beef were found in another recent review focussing exclusively on GHG emissions (Clune et al. 2017), and one on life-cycle assessments (Poore and Nemecek 2018). Poore and Nemecek (2018) amassed an extensive database that specifies both the hierarchy of emissions intensities and the variance with the production context (for example, by country and farming system).

The emissions intensities of red meat mean that its production has a disproportionate impact on total emissions (Godfray et al. 2018). For example, in the USA 4% of food sold (by weight) is beef, which accounts for 36% of food-related emissions (Heller and Keoleian 2015). Food-related emissions are therefore very sensitive to the amount and type of meat consumed. However, 100 g of beef has twice as much protein as the equivalent in cooked weight of beans, for example, and 2.5 times more iron. One can ingest only about 2.5 kg of food per day and not all food items are as dense in nutrition.

There is therefore *robust evidence with high agreement* that the mixture of foods eaten can have a highly significant impact on per capita carbon emissions, driven particularly through the amount of (especially grain-fed) livestock and products.

Given the rising costs of malnutrition in all its forms, a legitimate question is often asked: would a diet that promotes health through good nutrition also be one that mitigates GHG emissions? Whilst sustainable diets need not necessarily provide more nutrition, there is certainly significant overlap between those that are healthier (e.g., via eating more plant-based material and less livestock-based material), and eating the appropriate level of calories. In their systematic review, Nelson et al. (2016) conclude that, in general, a dietary pattern that is higher in plant-based foods, such as vegetables, fruits, whole grains, legumes, nuts, and seeds, and lower in animal-based foods is more health-promoting and is associated with lesser environmental impact (GHG emissions and energy, land, and water use) than is the current average 'meat-based' diet.

Recent FAO projections of food and agriculture to 2050 under alternative scenarios characterised by different degrees of sustainability, provide global-scale evidence that rebalancing diets is key to increasing the overall sustainability of food and agricultural systems world-wide. A 15% reduction of animal products in the diets of high-income countries by 2050 would contribute to containing the need to expand agricultural output due to upward global demographic trends. Not only would GHG emissions and the pressure on land and water be significantly reduced but the potential for low-income countries to increase the intake of animal-based food, with beneficial nutritional outcomes, could be enhanced (FAO 2018a). Given that higher-income countries typically have higher emissions per capita, results are particularly applicable in such places.

However, Springmann et al. (2018a) found that there are locally applicable upper bounds to the footprint of diets around the world, and for lower-income countries undergoing a nutrition transition, adopting 'Westernised' consumption patterns (over-consumption, large amounts of livestock produce, sugar and fat), even if in culturally applicable local contexts, would increase emissions. The global mitigation potential of healthy but low-emissions diets is discussed in detail in Section 5.5.2.1.

In summary, food system emissions are growing globally due to increasing population, income, and demand for animal-sourced products (*high confidence*). Diets are changing on average toward greater consumption of animal-based foods, vegetable oils and sugar/sweeteners (*high confidence*) (see also Chapter 2), with GHG emissions increasing due to greater amounts of animal-based products in diets (*robust evidence, medium agreement*).

5.5 Mitigation options, challenges and opportunities

The IPCC AR5 WG III concluded that mitigation in agriculture, forestry, and land use (AFOLU) is key to limit climate change in the 21st century, in terms of mitigation of non-CO_2 GHGs, which are predominately emitted in AFOLU, as well as in terms of land-based carbon sequestration. Wollenberg et al. (2016) highlighted the need to include agricultural emissions explicitly in national mitigation targets and plans, as a necessary strategy to meet the 2°C goal of the Paris Agreement. This chapter expands on these key findings to document how mitigation in the entire food system, from farm gate to consumer, can contribute to reaching the stated global mitigation goals, but in a context of improved food security and nutrition. To put the range of mitigation potential of food systems in context, it is worth noting that emissions from crop and livestock are expected to increase by 30–40% from present to 2050, under business-as-usual scenarios that include efficiency improvements as well as dietary changes linked to increased income per capita (FAO 2018a; Tubiello et al. 2014). Using current emissions estimates in this chapter and Chapter 2, these increases translate into projected GHG emissions from agriculture of 8–9 Gt CO_2-eq yr^{-1} by 2050 (*medium confidence*).

The AR5 ranked mitigation measures from simple mechanisms such as improved crop and livestock management (Smith et al. 2014) to more complex carbon dioxide reduction interventions, such as afforestation, soil carbon storage and biomass energy projects with carbon capture and storage (BECCS). The AR5 WGIII AFOLU chapter (Smith et al. 2014) identified two primary categories of mitigation pathways from the food system:

Supply side: Emissions from agricultural soils, land-use change, land management, and crop and livestock practices can be reduced and terrestrial carbon stocks can be increased by increased production efficiencies and carbon sequestration in soils and biomass, while emissions from energy use at all stages of the food system can be reduced through improvements in energy efficiency and fossil fuel substitution with carbon-free sources, including biomass.

Demand side: GHG emissions could be mitigated by changes in diet, reduction in food loss and waste, and changes in wood consumption for cooking.

In this chapter, supply-side mitigation practices include land-use change and carbon sequestration in soils and biomass in both crop and livestock systems. Cropping systems practices include improved land and fertiliser management, land restoration, biochar applications, breeding for larger root systems, and bridging yield gaps (Dooley and Stabinsky 2018). Options for mitigation in livestock systems include better manure management, improved grazing land management, and better feeding practices for animals. Agroforestry also is a supply-side mitigation practice. Improving efficiency in supply chains is a supply-side mitigation measure.

Demand-side mitigation practices include dietary changes that lead to reduction of GHG emissions from production and changes in land use that sequester carbon. Reduction of food loss and waste can contribute to mitigation of GHGs on both the supply and demand sides. See Section 5.7 and Chapter 7 for the enabling conditions needed to ensure that these food system measures would deliver their potential mitigation outcomes.

5.5.1 Supply-side mitigation options

The IPCC AR5 identified options for GHG mitigation in agriculture, including cropland management, restoration of organic soils, grazing land management and livestock, with a total mitigation potential of 1.6–4.6 $GtCO_2$-eq yr^{-1} by 2030 (compared to baseline emissions in the same year), at carbon prices from 20 to 100 USD per tCO_2-eq (Smith et al. 2014). Reductions in GHG emissions intensity (emissions per unit product) from livestock and animal products can also be a means to achieve reductions in absolute emissions in specific contexts and with appropriate governance (*medium confidence*). Agroforestry mitigation practices include rotational woodlots, long-term fallow, and integrated land use.

Emissions from food systems can be reduced significantly by the implementation of practices that reduce carbon dioxide, methane, and nitrous oxide emissions from agricultural activities related to the production of crops, livestock, and aquaculture. These include implementation of more sustainable and efficient crop and livestock production practices aimed at reducing the amount of land needed per output (reductions in GHG emissions intensity from livestock and animal production can support reductions in absolute emissions if total production is constrained), bridging yield gaps, implementing better feeding practices for animals and fish in aquaculture, and better manure management (FAO 2019a). Practices that promote soil improvements and carbon sequestration can also play an important role. In the South America region, reduction of deforestation, restoration of degraded pasture areas, and adoption of agroforestry and no-till agricultural techniques play a major role in the nation's voluntary commitments to reduce GHG emissions in the country's mitigation activities (Box 5.4).

The importance of supply-side mitigation options is that these can be directly applied by food system actors (farmers, processors, retailers) and can contribute to improved livelihoods and income generation. Recognising and empowering farming system actors with the right incentives and governance systems will be crucial to increasing the adoption rates of effective mitigation practices and to build convincing cases for enabling GHG mitigation (Section 5.7 and Chapter 7).

Box 5.4 | Towards sustainable intensification in South America

Reconciling the increasing global food demand with limited land resources and low environmental impact is a major global challenge (FAO 2018a; Godfray and Garnett 2014; Yao et al. 2017). South America has been a significant contributor of the world's agricultural production growth in the last three decades (OECD and FAO 2015), driven partly by increased export opportunities for specific commodities, mainly soybeans and meat (poultry, beef and pork).

Agricultural expansion, however, has driven profound landscape transformations in the region, particularly between the 1970s and early 2000s, contributing to increased deforestation rates and associated GHG emissions. High rates of native vegetation conversion were found in Argentina, Bolivia, Brazil, Colombia, Ecuador, Paraguay and Peru (FAO 2016b; Graesser et al. 2015), threatening ecologically important biomes, such as the Amazon, the savannas (Cerrado, Chacos and Lannos), the Atlantic Rainforest, the Caatinga, and the Yungas. The Amazon biome is a particularly sensitive biome as it provides crucial ecosystem services including biodiversity, hydrological processes (through evapotranspiration, cloud formation, and precipitation), and biogeochemical cycles (including carbon) (Bogaerts et al. 2017; Fearnside 2015; Beuchle et al. 2015; Grecchi et al. 2014; Celentano et al. 2017; Soares-Filho et al. 2014; Nogueira et al. 2018). Further, deforestation associated with commodity exports has not led to inclusive socioeconomic development, but rather has exacerbated social inequality and created more challenging living conditions for lower-income people (Celentano et al. 2017). Nor has it avoided increased hunger of local populations in the last few years (FAO 2018b).

In the mid-2000s, governments, food industries, NGOs, and international programmes joined forces to put in place important initiatives to respond to the growing concerns about the environmental impacts of agricultural expansion in the region (Negra et al. 2014; Finer et al. 2018). Brazil led regional action by launching the Interministerial Plan of Action for Prevention and Control of Deforestation of the Legal Amazon[2] (PPCDAm), associated with development of a real-time deforestation warning system. Further, Brazil built capacity to respond to alerts by coordinated efforts of ministries, the federal police, the army and public prosecution (Negra et al. 2014; Finer et al. 2018).

Other countries in the region have also launched similar strategies, including a zero-deforestation plan in Paraguay in 2004 (Gasparri and de Waroux 2015), and no-deforestation zones in Argentina in 2007 (Garcia Collazo et al. 2013). Peru also developed the National System of Monitoring and Control, led by the National Forest Service and Wildlife Authority (SERFOR), to provide information and coordinate response to deforestation events, and Colombia started producing quarterly warning reports on active fronts of deforestation in the country (Finer et al. 2018).

Engagement of the food industry and NGOs, particularly through the Soy Moratorium (from 2006) and Beef Moratorium (from 2009) also contributed effectively to keep deforestation at low historical rates in the regions where they were implemented (Nepstad et al. 2014 and Gibbs et al. 2015). In 2012, Brazil also created the national land registry system (SICAR), a georeferenced database, which allows monitoring of farms' environmental liability in order to grant access to rural credit. Besides the governmental schemes, funding agencies and the Amazon Fund provide financial resources to assist smallholder farmers to comply with environmental regulations (Jung et al. 2017).

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[2] The Legal Amazon is a Brazilian region of 501.6 Mha (about 59% of the Brazilian territory) that contains all the Amazon but also 40% of the Cerrado and 40% of the Pantanal biomes, with a total population of 25.47 million inhabitants.

Box 5.4 (continued)

Nevertheless, Azevedo et al. (2017) argue that the full potential of these financial incentives has not been achieved, due to weak enforcement mechanisms and limited supporting public policies. Agricultural expansion and intensification have complex interactions with deforestation. While mechanisms have been implemented in the region to protect native forests and ecosystems, control of deforestation rates require stronger governance of natural resources (Ceddia et al. 2013 and Oliveira and Hecht 2016), including monitoring programmes to evaluate fully the results of land-use policies in the region.

Public and private sector actions resulted in a reduction of the Brazilian legal Amazon deforestation rate from 2.78 Mha yr^{-1} in 2004, to about 0.75 Mha yr^{-1} (ca. 0.15%) in 2009 (INPE 2015), oscillating from 0.46 Mha and 0.79 Mha (2016) since then (INPE 2018; Boucher and Chi 2018). The governmental forest protection scheme was also expanded to other biomes. As a result, the Brazilian Cerrado deforestation was effectively reduced from 2.9 Mha yr^{-1} in 2004 to an average of 0.71 Mha yr^{-1} in 2016–2017 (INPE 2018).

Overall, deforestation rates in South America have declined significantly, with current deforestation rates being about half of rates in the early 2000s (FAOSTAT 2018). However, inconsistent conservation policies across countries (Gibbs et al. 2015) and recent hiccups (Curtis et al. 2018) indicate that deforestation control still requires stronger reinforcement mechanisms (Tollefson 2018). Further, there are important spill-over effects that need coordinated international governance. Curtis et al. (2018) and Dou et al. (2018) point out that, although the Amazon deforestation rate decreased in Brazil, it has increased in other regions, particularly in South Asia, and in other countries in South America, resulting in nearly constant deforestation rates worldwide.

Despite the reduced expansion rates into forest land, agricultural production continues to rise steadily in South America, relying on increasing productivity and substitution of extensive pastureland by crops. The average soybean and maize productivity in the region increased from 1.8 and 2.0 t ha^{-1} in 1990 to 3.0 and 5.0 t ha^{-1}, respectively, in 2015 (FAOSTAT 2018). Yet, higher crop productivity was not enough to meet growing demand for cereals and oilseeds and cultivation continued to expand, mainly on grasslands (Richards 2015). The reconciliation of this expansion with higher demand for meat and dairy products was carried out through the intensification of livestock systems (Martha et al. 2012). Nevertheless, direct and indirect deforestation still occurs, and recently deforestation rates have increased (INPE 2018), albeit they remain far smaller than observed in the 2000–2010 period.

The effort towards sustainable intensification has also been incorporated in agricultural policies. In Brazil, for instance, the reduction of deforestation, the restoration of degraded pasture areas, the adoption of integrated agroforestry systems[3] and no-till agricultural techniques play a major role in the nation's voluntary commitments to reduce GHG emissions in the country's NAMAs (Mozzer 2011) and NDCs (Silva Oliveira et al. 2017; Rochedo et al. 2018). Such commitment under the UNFCCC is operationalised through the Low Carbon Agriculture Plan (ABC),[4] which is based on low interest credit for investment in sustainable agricultural technologies (Mozzer 2011). Direct pasture restoration and integrated systems reduce area requirements (Strassburg et al. 2014), and increase organic matter (Gil et al. 2015; Bungenstab 2012; Maia et al. 2009), contributing to overall lifecycle emissions reduction (Cardoso et al. 2016; de Oliveira Silva et al. 2016). Also, increased adoption of supplementation and feedlots, often based on agroindustrial co-products and agricultural crop residues are central to improve productivity and increase climate resilience of livestock systems (Mottet et al. 2017a; van Zanten et al. 2018).

Despite providing clear environmental and socio-economic co-benefits, including improved resource productivity, socio-environmental sustainability and higher economic competitiveness, implementation of the Brazilian Low Carbon Agriculture Plan is behind schedule (Köberle et al. 2016). Structural inefficiencies related to the allocation and distribution of resources need to be addressed to put the plan on track to meet its emissions reduction targets. Monitoring and verification are fundamental tools to guarantee the successful implementation of the plan.

Overall, historical data and projections show that South America is one of the regions of the world with the highest potential to increase crop and livestock production in the coming decades in a sustainable manner (Cohn et al. 2014), increasing food supply to more densely populated regions in Asia, Middle East and Europe. However, a great and coordinated effort is required from governments, industry, traders, scientists and the international community to improve planning, monitoring and innovation to guarantee sustainable intensification of its agricultural systems, contribution to GHG mitigation, and conservation of the surrounding environment (Negra et al. 2014; Curtis et al. 2018 and Lambin et al. 2018).

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[3] Integrated agroforestry systems are agricultural systems that strategically integrate two or more components among crops, livestock and forestry. The activities can be in consortium, succession or rotation in order to achieve overall synergy.

[4] ABC – *Agricultura de Baixo Carbono* in Portuguese.

5.5.1.1 Greenhouse gas mitigation in croplands and soils

The mitigation potential of agricultural soils, cropland and grazing land management has been the subject of much research and was thoroughly summarised in the AR5 (Smith et al. 2014) (see also Chapter 2, Section 2.5.1 and Chapter 6, Section 6.3.1). Key mitigation pathways are related to practices reducing nitrous oxide emissions from fertiliser applications, reducing methane emissions from paddy rice, reducing both gases through livestock manure management and applications, and sequestering carbon or reducing its losses, with practices for improving grassland and cropland management identified as the largest mitigation opportunities. Better monitoring reporting and verification (MRV) systems are currently needed for reducing uncertainties and better quantifying the actual mitigation outcomes of these activities.

New work since AR5 has focused on identifying pathways for the reductions of GHG emissions from agriculture to help meet Paris Agreement goals (Paustian et al. 2016 and Wollenberg et al. 2016). Altieri and Nicholls (2017) have characterised mitigation potentials from traditional agriculture. Zomer et al. (2017) have updated previous estimates of global carbon sequestration potential in cropland soils. Mayer et al. (2018) converted soil carbon sequestration potential through agricultural land management into avoided temperature reductions. Fujisaki et al. (2018) identify drivers to increase soil organic carbon in tropical soils. For discussion of integrated practices such as sustainable intensification, conservation agriculture and agroecology, see Section 5.6.4.

Paustian et al. (2016) developed a decision-tree for facilitating implementation of mitigation practices on cropland and described the features of key practices. They observed that most individual mitigation practices will have a small effect per unit of land, and hence they need to be combined and applied at large scales for their impact to be significant. Examples included aggregation of cropland practices (for example, organic amendments, improved crop rotations and nutrient management and reduced tillage) and grazing land practices (e.g., grazing management, nutrient and fire management and species introduction) that could increase net soil carbon stocks while reducing emissions of N_2O and CH_4.

However, it is well-known that the portion of projected mitigation from soil carbon stock increase (about 90% of the total technical potential) is impermanent. It would be effective for only 20–30 years due to saturation of the soil capacity to sequester carbon, whereas non-CO_2 emission reductions could continue indefinitely. **'Technical potential'** is the maximum amount of GHG mitigation achievable through technology diffusion.

Biochar application and management towards enhanced root systems are mitigation options that have been highlighted in recent literature (Dooley and Stabinsky 2018; Hawken 2017; Paustian et al. 2016; Woolf et al. 2010 and Lenton 2010).

5.5.1.2 Greenhouse gas mitigation in livestock systems

The technical options for mitigating GHG emissions in the livestock sector have been the subject of recent reviews (Mottet et al. 2017b; Hristov et al. 2013a,b; Smithers 2015; Herrero et al. 2016a; Rivera-Ferre et al. 2016b) (Figure 5.11). They can be classified as either targeting reductions in enteric methane; reductions in nitrous oxide through manure management; sequestering carbon in pastures; implementation of best animal husbandry and management practices, which would have an effect on most GHG; and land-use practices that also help sequester carbon. Excluding land-use practices, these options have a technical mitigation potential ranging 0.2–2.4 $GtCO_2$-eq yr^{-1} (Herrero et al. 2016a; FAO 2007) (Chapters 2 and 6.)

The opportunities for carbon sequestration in grasslands and rangelands may be significant (Conant 2010), for instance, through changes in grazing intensity or manure recycling aimed at maintaining grassland productivity (Hirata et al. 2013). Recent studies have questioned the economic potential of such practices in regard to whether they could be implement at scale for economic gain (Garnett et al. 2017; Herrero et al. 2016a and Henderson et al. 2015). For instance, Henderson et al. (2015) found economic potentials below 200 $MtCO_2$-eq yr^{-1}. Carbon sequestration can occur in situations where grasslands are highly degraded (Garnett 2016). Carbon sequestration linked to livestock management could thus be considered as a co-benefit of well-managed grasslands, as well as a mitigation practice.

Different production systems will require different strategies, including the assessment of impacts on food security, and this has been the subject of significant research (e.g., Rivera-Ferre et al. 2016b). Livestock systems are heterogeneous in terms of their agroecological orientation (arid, humid or temperate/highland locations), livestock species (cattle, sheep, goats, pigs, poultry and others), structure (grazing only, mixed-crop-livestock systems, industrial systems, feedlots and others), level of intensification, and resource endowment (Robinson 2011).

The implementation of strategies presented in Figure 5.11 builds on this differentiation, providing more depth compared to the previous AR5 analysis. Manure management strategies are more applicable in confined systems, where manure can be easily collected, such as in pigs and poultry systems or in smallholder mixed crop-livestock systems. More intensive systems, with strong market orientation, such as dairy in the US, can implement a range of sophisticated practices like feed additives and vaccines, while many market-oriented dairy systems in tropical regions can improve feed digestibility by improving forage quality and adding larger quantities of concentrate to the rations. Many of these strategies can be implemented as packages in different systems, thus maximising the synergies between different options (Mottet et al. 2017b).

See the Supplementary Material Section SM5.5 for a detailed description of livestock mitigation strategies; synergies and trade-offs with other mitigation and adaptation options are discussed in Section 5.6.

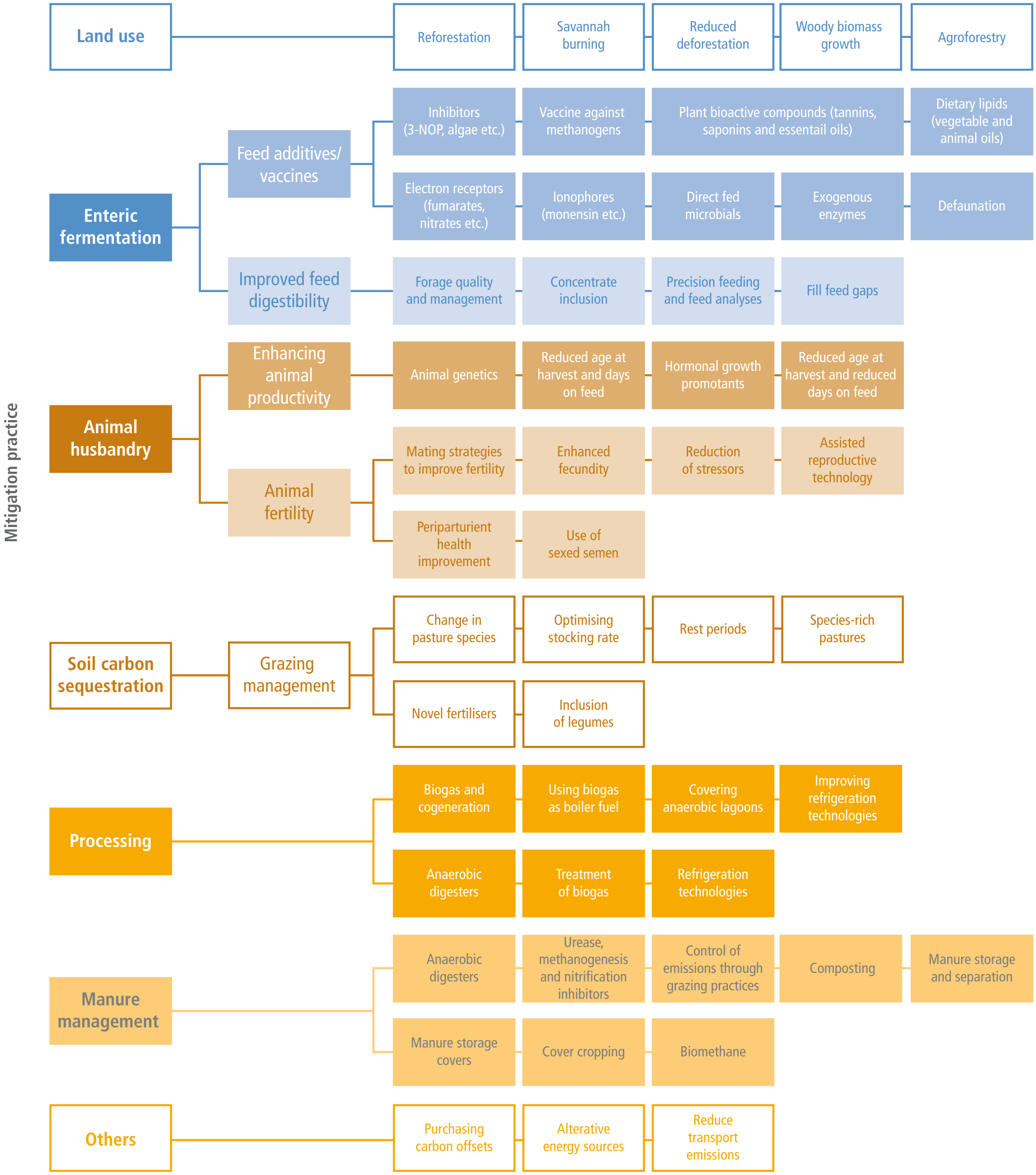


Figure 5.11 | Technical supply-side mitigation practices in the livestock sector (adapted from Hristov et al. 2013b; Herrero et al. 2016b and Smith et al. 2014).

5.5.1.3 Greenhouse gas mitigation in agroforestry

Agroforestry can curb GHG emissions of CO_2, CH_4, and N_2O in agricultural systems in both developed and developing countries (see Glossary for definition) (see Chapter 2, Section 2.5.1 and Figure 2.24). Soil carbon sequestration, together with biological N fixation, improved land health and underlying ecosystem services may be enhanced through agricultural lands management practices used by large-scale and smallholder farmers, such as incorporation of trees within farms or in hedges (manure addition, green manures, cover crops, etc.), whilst promoting greater soil organic matter and nutrients (and thus soil organic carbon) content and improve soil structure (Mbow et al. 2014b) (Table 5.5). The tree cover increases the microbial activity of the soil and increases the productivity of the grass under cover. CO_2 emissions are furthermore lessened indirectly, through lower rates of erosion due to better soil structure and more plant cover in diversified farming systems than in monocultures. There is great potential for increasing above-ground and soil carbon stocks, reducing soil erosion and degradation, and mitigating GHG emissions.

These practices can improve food security through increases in productivity and stability since they contribute to increased soil quality and water-holding capacity. Agroforestry provides economic, ecological, and social stability through diversification of species and products. On the other hand, trade-offs are possible when cropland is taken out of production mainly as a mitigation strategy.

Meta-analyses have been done on carbon budgets in agroforestry systems (Zomer et al. 2016; Chatterjee et al. 2018). In a review of 42 studies, (Ramachandran Nair et al. 2009) estimated carbon sequestration potentials of differing agroforestry systems. These include sequestration rates ranging from 954 (semi-arid); to 1431 (temperate); 2238 (sub-humid) and 3670 tCO_2 km^{-2} yr^{-1} (humid). The global technical potential for agroforestry is 0.1–5.7 Gt CO_2e yr^{-1} (Griscom et al. 2017; Zomer et al. 2016; Dickie et al. 2014) (Chapter 2, Section 2.5.1). Agroforestry-based carbon sequestration can be used to offset N_2O and CO_2 emissions from soils and increase methane sink strength compared to annual cropping systems (Rosenstock et al. 2014).

Agroforestry systems with perennial crops, such as coffee and cacao, may be more important carbon sinks than those that combine trees with annual crops. Brandt et al. (2018) showed that farms in semi-arid regions (300–600 mm precipitation) were increasing in tree cover due to natural regeneration and that the increased application of agroforestry systems were supporting production and reducing GHG emissions.

5.5.1.4 Integrated approaches to crop and livestock mitigation

Livestock mitigation in a circular economy. Novel technologies for increasing the integration of components in the food system are being devised to reduce GHG emissions. These include strategies that help decoupling livestock from land use. Work by van Zanten et al. (2018) shows that 7–23 g of animal protein per capita per day could be produced without livestock competing for vital arable land. This would imply a contraction of the land area utilised by the livestock sector, but also a more efficient use of resources, and would lead to land sparing and overall emissions reductions.

Pikaar et al. (2018) demonstrated the technical feasibility of producing microbial protein as a feedstuff from sewage that could replace use of feed crops such as soybean. The technical potential of this novel practice could replace 10–19% of the feed protein required, and would reduce cropland demand and associated emissions by 6–7%. These practices are, however, not economically feasible nor easily upscalable in most systems. Nonetheless, significant progress in Japan and South Korea in the reduction and use of food waste to increase efficiencies in livestock food chains has been achieved, indicating a possible pathway to progress elsewhere (FAO 2017; zu Ermgassen et al. 2016). Better understanding of biomass and food and feed wastes, value chains, and identification of mechanisms for reducing the transport and processing costs of these materials is required to facilitate larger-scale implementation.

Table 5.5 | Carbon sequestration potential for agroforestry (Mbow et al. 2014b).

Source	Carbon sequestration (tCO_2 km^{-2} yr^{-1}) (range)	Carbon stock (tCO_2 km^{-2}) (range)	Maximum rotation period (years)
Dominant parklands	183 (73–293)	12,257 (2091–25,983)	50
Rotational woodlots[a]	1,431 (807–2128)	6,789 (4257–9358)	5
Tree planting-windrows-home gardens	220.2 (146–293)	6,973 (–)	25
Long-term fallows, regrowth of woodlands in abandoned farms[b]	822 (80–2128)	5,761 (–)	25
Integrated land use	1,145 (367–2458)	28,589 (4404–83,676)	50
Soil carbon	330 (91–587)	33,286 (4771–110,100)	–

[a] May be classified as forestry on forest land, depending on the spatial and temporal characteristics of these activities.

[b] This is potentially not agroforestry, but forestry following abandonment of agricultural land.

Waste streams into energy. Waste streams from manure and food waste can be used for energy generation and thus reduction in overall GHG emissions in terms of recovered methane (for instance through anaerobic digestion) production (De Clercq et al. 2016) or for the production of microbial protein (Pikaar et al. 2018). Second-generation biorefineries, once the underlying technology is improved, may enable the generation of hydro-carbon from agricultural residues, grass, and woody biomass in ways that do not compete with food and can generate, along with biofuel, high-value products such as plastics (Nguyen et al. 2017). Second-generation energy biomass from residues may constitute a complementary income source for farmers that can increase their incentive to produce. Technologies include CHP (combined heat and power) or gas turbines, and fuel types such as biodiesel, biopyrolysis (i.e., high temperature chemical transformation of organic material in the absence of oxygen), torrefaction of biomass, production of cellulosic bioethanol and of bioalcohols produced by other means than fermentation, and the production of methane by anaerobic fermentation. (Nguyen et al. 2017).

Technology for reducing fossil fuel inputs. Besides biomass and bioenergy, other forms of renewable energy substitution for fossil fuels (e.g., wind, solar, geothermal, hydro) are already being applied on farms throughout the supply chain. Energy efficiency measures are being developed for refrigeration, conservation tillage, precision farming (e.g., fertiliser and chemical application and precision irrigation).

Novel technologies. Measures that can reduce livestock emissions given continued research and development include methane and nitrification inhibitors, methane vaccines, targeted breeding of lower-emitting animals, and genetically modified grasses with higher sugar content. New strategies to reduce methanogenesis include supplementing animal diets with antimethanogenic agents (e.g., 3-NOP, algae, chemical inhibitors such as chloroform) or supplementing with electron acceptors (e.g., nitrate) or dietary lipids. These could potentially contribute, once economically feasible at scale, to significant reductions of methane emissions from ruminant livestock. A well-tested compound is 3-nitrooxypropanol (3-NOP), which was shown to decrease methane by up to 40% when incorporated in diets for ruminants (Hristov et al. 2015).

Whilst these strategies may become very effective at reducing methane, they can be expensive and also impact on animal performance and/or welfare (Llonch et al. 2017). The use of novel fertilisers and/or plant species that secrete biological nitrification inhibitors also have the potential to significantly reduce N_2O emissions from agricultural soils (Subbarao et al. 2009; Rose et al. 2018).

Economic mitigation potentials of crop and livestock sectors. Despite the large technical mitigation potential of the agriculture sector in terms of crop and livestock activities, its economic potential is relatively small in the short term (2030) and at modest carbon prices (less than 20 USD tC^{-1}). For crop and soil management practices, it is estimated that 1.0–1.5 $GtCO_2$-eq yr^{-1} could be a feasible mitigation target at a carbon price of 20 USD tC^{-1} (Frank et al. 2018, 2017; Griscom et al. 2016; Smith et al. 2013; Wollenberg et al. 2016). For the livestock sector, these estimates range from 0.12–0.25 $GtCO_2$-eq yr^{-1} at similar carbon prices (Herrero et al. 2016c; Henderson et al. 2017). But care is needed in comparing crop and livestock economic mitigation potentials due to differing assumptions.

Frank et al. (2018) recently estimated that the economic mitigation potential of non-CO_2 emissions from agriculture and livestock to 2030 could be up to four times higher than indicated in the AR5, if structural options such as switching livestock species from ruminants to monogastrics, or allowing for flexibility to relocate production to more efficient regions were implemented, at the same time as the technical options such as those described above. At higher carbon prices (i.e., at about 100 USD tC^{-1}), they found a mitigation potential of supply-side measures of 2.6 $GtCO_2$-eq yr^{-1}.

In this scenario, technical options would account for 38% of the abatement, while another 38% would be obtained through structural changes, and a further 24% would be obtained through shifts in consumption caused by food price increases. Key to the achievement of this mitigation potential lay in the livestock sector, as reductions in livestock consumption, structural changes and implementation of technologies in the sector had some of the highest impacts. Regions with the highest mitigation potentials were Latin America, China and Sub-Saharan Africa. The large-scale implementability of such proposed sweeping changes in livestock types and production systems is likely very limited as well as constrained by long-established socio-economic, traditional and cultural habits, requiring significant incentives to generate change.

In summary, supply-side practices can contribute to climate change mitigation by reducing crop and livestock emissions, sequestering carbon in soils and biomass, and by decreasing emissions intensity within sustainable production systems (*high confidence*). The AR5 estimated the total economic mitigation potential of crop and livestock activities as 1.5–4.0 $GtCO_2$-eq yr^{-1} by 2030 at prices ranging from 20–100 USD tCO_2-eq (*high confidence*). Options with large potential for GHG mitigation in cropping systems include soil carbon sequestration (at decreasing rates over time), reductions in N_2O emissions from fertilisers, reductions in CH_4 emissions from paddy rice, and bridging of yield gaps. Options with large potential for mitigation in livestock systems include better grazing land management, with increased net primary production and soil carbon stocks, improved manure management, and higher-quality feed. Reductions in GHG emissions intensity (emissions per unit product) from livestock can support reductions in absolute emissions, provided appropriate governance structures to limit total production are implemented at the same time (*medium confidence*).

5.5.1.5 Greenhouse gas mitigation in aquaculture

Barange et al. (2018) provide a synthesis of effective options for GHG emissions reduction in aquaculture, including reduction of emissions from production of feed material, replacement of fish-based feed ingredients with crop-based ingredients; reduction of emissions from feed mill energy use, improvement of feed conversion rates, improvement of input use efficiency, shift of energy supply (from high-carbon fossil fuels to low-carbon fossil fuels or renewables), and improvement of fish health. Conversion of 25% of total aquaculture area to integrated aquaculture-agriculture ponds (greening aquaculture) has the potential to sequester 95.4 million tonnes of carbon per year (Ahmed et al. 2017).

Proposed mitigation in aquaculture includes avoided deforestation. By halting annual mangrove deforestation in Indonesia, associated total emissions would be reduced by 10–31% of estimated annual emissions from the land-use sector at present (Murdiyarso et al. 2015). Globally, 25% mangrove regeneration could sequester 0.54–0.65 million tonnes of carbon per year (Ahmed et al. 2017) of which 0.17–0.21 million tonnes could be through integrated or organic shrimp culture (Ahmed et al. 2018).

5.5.1.6 Cellular agriculture

The technology for growing muscle tissue in culture from animal stem cells to produce meat, for example, 'cultured', 'synthetic', 'in vitro' or 'hydroponic' meat could, in theory, be constructed with different characteristics and be produced faster and more efficiently than traditional meat (Kadim et al. 2015). Cultured meat (CM) is part of so-called cellular agriculture, which includes production of milk, egg white and leather from industrial cell cultivation (Stephens et al. 2018). CM is produced from muscle cells extracted from living animals, isolation of adult skeletal muscle stem cells (myosatellite cells), placement in a culture medium which allow their differentiation into myoblasts and then, through another medium, generation of myocytes which coalesce into myotubes and grow into strands in a stirred-tank bioreactor (Mattick et al. 2015).

Current technology enables the creation of beef hamburgers, nuggets, steak chips or similar products from meat of other animals, including wild species, although production currently is far from being economically feasible. Nonetheless, by allowing bioengineering from the manipulation of the stem cells and nutritive culture, CM allows for reduction of harmful fatty acids, with advantages such as reduced GHG emissions, mostly indirectly through reduced land use (Bhat et al. 2015; Kumar et al. 2017b).

Tuomisto and de Mattos (2011) made optimistic technological assumptions, relying on cyanobacteria hydrolysate nutrient source, and produced the lowest estimates on energy and land use. Tuomisto and de Mattos (2011) conducted a lifecycle assessment that indicates that cultured meat could have less than 60% of energy use and 1% of land use of beef production and it would have lower GHG emissions than pork and poultry as well. Newer estimates (Alexander et al. 2017; Mattick et al. 2015) indicate a trade-off between industrial energy consumption and agricultural land requirements of conventional and cultured meat and possibly higher GWP than pork or poultry due to higher energy use. The change in proportion of CO_2 versus CH_4 could have important implications in climate change projections and, depending on decarbonisation of the energy sources and climate change targets, cultured meat may be even more detrimental than exclusive beef production (Lynch and Pierrehumbert 2019).

Overall, as argued by Stephens et al. (2018), cultured meat is an 'as-yet undefined ontological object' and, although marketing targets people who appreciate meat but are concerned with animal welfare and environmental impacts, its market is largely unknown (Bhat et al. 2015 and Slade 2018). In this context it will face the competition of imitation meat (meat analogues from vegetal protein) and insect-derived products, which have been evaluated as more environmentally friendly (Alexander et al. 2017) and it may be considered as being an option for a limited resource world, rather than a mainstream solution. Besides, as the commercial production process is still largely undefined, its actual contribution to climate change mitigation and food security is largely uncertain and challenges are not negligible. Finally, it is important to understand the systemic nature of these challenges and evaluate their social impacts on rural populations due to transforming animal agriculture into an industrialised activity and its possible rebound effects on food security, which are still understudied in the literature.

Studies are needed to improve quantification of mitigation options for supply chain activities.

5.5.2 Demand-side mitigation options

Although population growth is one of the drivers of global food demand and the resulting environmental burden, demand-side management of the food system could be one of the solutions to curb climate change. Avoiding food waste during consumption, reducing over-consumption, and changing dietary preferences can contribute significantly to providing healthy diets for all, as well as reducing the environmental footprint of the food system. The number of studies addressing this issue have increased in the last few years (Chapter 2). (See Section 5.6 for synergies and trade-offs with health and Section 5.7 for discussion of Just Transitions.)

5.5.2.1 Mitigation potential of different diets

A systematic review found that higher consumption of animal-based foods was associated with higher estimated environmental impact, whereas increased consumption of plant-based foods was associated with an estimated lower environmental impact (Nelson et al. 2016). Assessment of individual foods within these broader categories showed that meat – especially ruminant meat (beef and lamb) – was consistently identified as the single food with the greatest impact on the environment, on a global basis, most often in terms of GHG emissions and/or land use.

Figure 5.12 shows the technical mitigation potentials of some scenarios of alternative diets examined in the literature. Stehfest et al. (2009) were among the first to examine these questions. They found that under the most extreme scenario, where no animal products are consumed at all, adequate food production in 2050 could be achieved on less land than is currently used, allowing considerable forest regeneration, and reducing land-based GHG emissions to one third of the reference 'business-as-usual' case for 2050, a reduction of 7.8 $GtCO_2$-eq yr^{-1}. Springmann et al. (2016b) recently estimated similar emissions reduction potential of 8 $GtCO_2$-eq yr^{-1} from a vegan diet without animal-sourced foods. This defines the upper bound of the technical mitigation potential of demand side measures.

Herrero et al. (2016a) reviewed available options, with a specific focus on livestock products, assessing technical mitigation potential

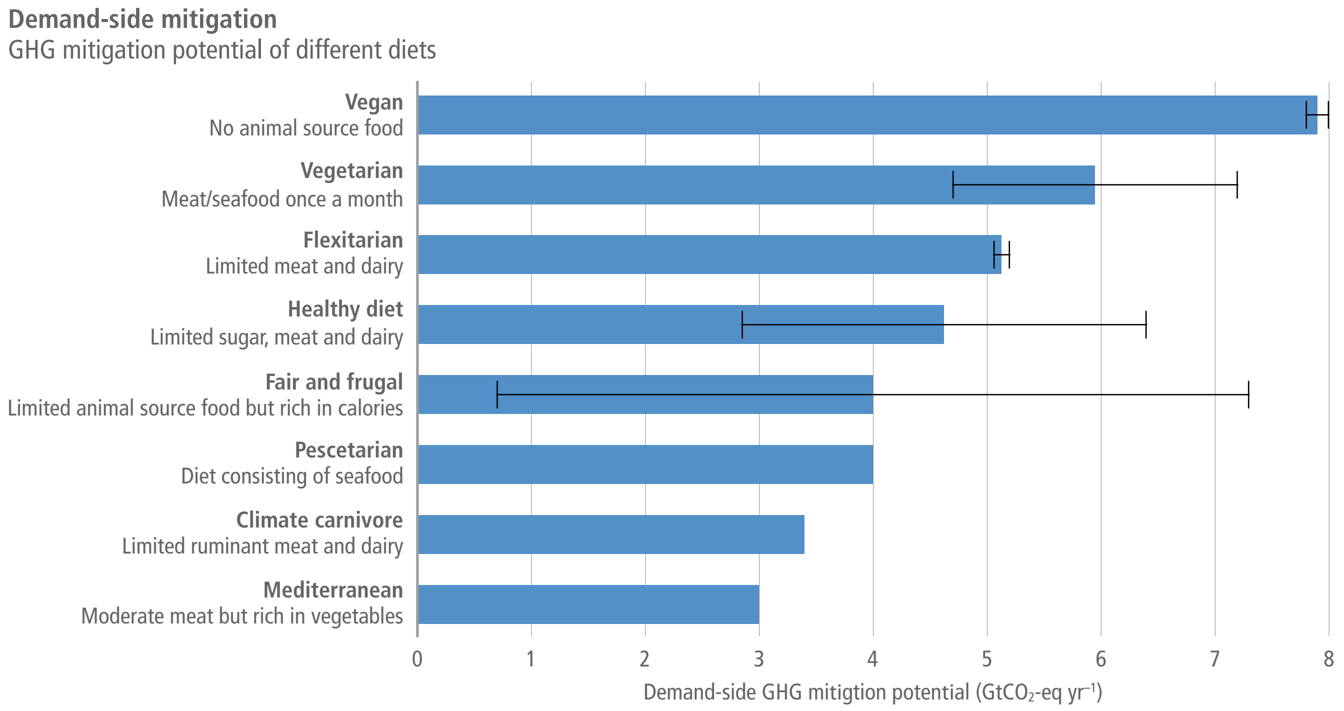


Figure 5.12 | Technical mitigation potential of changing diets by 2050 according to a range of scenarios examined in the literature. Estimates indicate technical potential only and include additional effects of carbon sequestration from land-sparing. Data without error bars are from one study only.

All diets need to provide a full complement of nutritional quality, including micronutrients (FAO et al. 2018).

Vegan: Completely plant-based (Springmann et al. 2016b; Stehfest et al. 2009).

Vegetarian: Grains, vegetables, fruits, sugars, oils, eggs and dairy, and generally at most one serving per month of meat or seafood (Springmann et al. 2016b; Tilman and Clark 2014; Stehfest et al. 2009).

Flexitarian: 75% of meat and dairy replaced by cereals and pulses; at least 500 g per day fruits and vegetables; at least 100 g per day of plant-based protein sources; modest amounts of animal-based proteins and limited amounts of red meat (one portion per week), refined sugar (less than 5% of total energy), vegetable oils high in saturated fat, and starchy foods with relatively high glycaemic index (Springmann et al. 2018a; Hedenus et al. 2014).

Healthy diet: Based on global dietary guidelines for consumption of red meat, sugar, fruits and vegetables, and total energy intake (Springmann et al. 2018a; Bajželj et al. 2014).

Fair and frugal: Global daily per-capita calorie intake of 2800 kcal/cap/day (11.7 MJ/cap/day), paired with relatively low level of animal products (Smith et al. 2013).

Pescetarian: Vegetarian diet that includes seafood (Tilman and Clark 2014).

Climate carnivore: 75% of ruminant meat and dairy replaced by other meat (Hedenus et al. 2014).

Mediterranean: Vegetables, fruits, grains, sugars, oils, eggs, dairy, seafood, moderate amounts of poultry, pork, lamb and beef (Tilman and Clark 2014).

across a range of scenarios, including 'no animal products', 'no meat', 'no ruminant meat', and 'healthy diet' (reduced meat consumption). With regard to 'credible low-meat diets', where reduction in animal protein intake was compensated by higher intake of pulses, emissions reductions by 2050 could be in the 4.3–6.4 GtCO$_2$-eq yr^{-1}, compared to a business-as-usual scenario. Of this technical potential, 1–2 GtCO$_2$-eq yr^{-1} come from reductions of mostly non-CO$_2$ GHG within the farm gate, while the remainder was linked to carbon sequestration on agricultural lands no longer needed for livestock production. When the transition to a low-meat diet reduces the agricultural area required, land is abandoned, and the re-growing vegetation can take up carbon until a new equilibrium is reached. This is known as the land-sparing effect.

Other studies have found similar results for potential mitigation linked to diets. For instance, Smith et al. (2013) analysed a dietary change scenario that assumed a convergence towards a global daily per-capita calorie intake of 2800 kcal per person per day (11.7 MJ per person per day), paired with a relatively low level of animal product supply, estimated technical mitigation potential in the range 0.7–7.3 GtCO$_2$-eq yr^{-1} for additional variants including low or high-yielding bioenergy, 4.6 GtCO$_2$-eq yr^{-1} if spare land is afforested.

Bajželj et al. (2014) developed different scenarios of farm systems change, waste management, and dietary change on GHG emissions coupled to land use. Their dietary scenarios were based on target kilocalorie consumption levels and reductions in animal product consumption. Their scenarios were 'healthy diet'; healthy diet with 2500 kcal per person per day in 2050; corresponding to technical mitigation potentials in the range 5.8 and 6.4 GtCO$_2$-eq yr^{-1}.

Hedenus et al. (2014) explored further dietary variants based on the type of livestock product. 'climate carnivore', in which 75% of the baseline-consumption of ruminant meat and dairy was replaced by pork and poultry meat, and 'flexitarian', in which 75% of the baseline-consumption of meat and dairy was replaced by pulses and cereal products. Their estimates of technical mitigation potentials by 2050 ranged 3.4–5.2 $GtCO_2$-eq yr^{-1}, the high end achieved under the flexitarian diet. Finally, Tilman and Clark (2014) used stylised diets as variants that included 'peseatarian', 'Mediterranean', 'vegetarian', compared to a reference diet, and estimated technical mitigation potentials within the farm gate of 1.2–2.3 $GtCO_2$-eq yr^{-1}, with additional mitigation from carbon sequestration on spared land ranging 1.8–2.4 $GtCO_2$-eq yr^{-1}.

Studies have defined dietary mitigation potential as, for example, 20 kg per person per week CO_2-eq for Mediterranean diet, versus 13 kg per person per week CO_2-eq for vegan (Castañé and Antón 2017). Rosi et al. (2017) developed seven-day diets in Italy for about 150 people defined as omnivore 4.0 ± 1.0; ovo-lacto-veggie 2.6 ± 0.6; and vegan 2.3 ± 0.5 kg CO_2-eq per capita per day.

Importantly, many more studies that compute the economic and calorie costs of these scenarios are needed. Herrero et al. (2016a) estimated that once considerations of economic and calorie costs of their diet-based solutions were included, the technical range of 4.3–6.4 $GtCO_2$-eq yr^{-1} in 2050 was reduced to 1.8–3.4 $GtCO_2$-eq yr^{-1} when implementing a GHG tax ranging from 20–100 USD tCO_2. While caloric costs where low below 20 USD tCO_2, they ranged from 27–190 kcal per person per day under the higher economic potential, thus indicating possible negative trade-offs with food security.

In summary, demand-side changes in food choices and consumption can help to achieve global GHG mitigation targets (*high confidence*). Low-carbon diets on average tend to be healthier and have smaller land footprints. By 2050, technical mitigation potential of dietary changes range from 2.7–6.4 $GtCO_2$-eq yr^{-1} for assessed diets (*high confidence*). At the same time, the economic potential of such solutions is lower, ranging from 1.8–3.4 $GtCO_2$-eq yr^{-1} at prices of 20–100 USD tCO_2, with caloric costs up to 190 kcal per person per day. The feasibility of how to create economically viable transitions to more sustainable and healthy diets that also respect food security requirements needs to be addressed in future research.

5.5.2.2 Role of dietary preferences

Food preference is an inherently cultural dimension that can ease or hinder transformations to food systems that contribute to climate change mitigation. Consumer choice and dietary preferences are guided by social, cultural, environmental, and traditional factors as well as economic growth. The food consumed by a given group conveys cultural significance about social hierarchy, social systems and human-environment relationships (Herforth and Ahmed 2015).

As suggested by Springmann et al. (2018a), per capita dietary emissions will translate into different realised diets, according to regional contexts including cultural and gendered norms (e.g., among some groups, eating meat is perceived as more masculine (Ruby and Heine 2011). In some cases, women and men have different preferences in terms of food, with women reporting eating healthier food (Imamura et al. 2015; Kiefer et al. 2005; Fagerli and Wandel 1999): these studies found that men tend to eat more meat, while women eat more vegetables, fruits and dairy products (Kanter and Caballero 2012).

Food preferences can change over time, with the nutrition transition from traditional diets to high-meat, high-sugar, high-saturated fat diets being a clear example of significant changes occurring in a short period of time. Meat consumption per capita consistently responds to income with a saturating trend at high income levels (Sans and Combris 2015; Vranken et al. 2014). Some emerging economies have rapidly increased demand for beef, leading to pressure on natural resources (Bowles et al. 2019). In another example, by reducing beef consumption between 2005 and 2014, Americans avoided approximately 271 million metric tonnes of emissions (CO_2-eq) (NRDC 2017). Attending farmers markets or buying directly from local producers has been shown to change worldviews (Kerton and Sinclair 2010), and food habits towards healthier diets (Pascucci et al. 2011) can be advanced through active learning (Milestad et al. 2010).

Regarding the options to reduce meat intake in developed countries, research shows that there is an apparent sympathy of consumers for meat reduction due to environmental impacts (Dagevos and Voordouw 2013), which has not been exploited. Social factors that influence reducing meat consumption in New Zealand include the need for better education or information dispersal regarding perceived barriers to producing meat-reduced/less meals; ensuring there is sensory or aesthetic appeal; and placing emphasis on human health or nutritional benefits (Tucker 2018).

Different and complementary strategies can be used in parallel for different consumer's profiles to facilitate step-by-step changes in the amounts and the sources of protein consumed. In the Netherlands, a nationwide sample of 1083 consumers were used to study their dietary choices toward smaller portions of meat, smaller portions using meat raised in a more sustainable manner, smaller portions and eating more vegetable protein, and meatless meals with or without meat substitutes. Results showed that strategies to change meat eating frequencies and meat portion sizes appeared to overlap and that these strategies can be applied to address consumers in terms of their own preferences (de Boer et al. 2014).

5.5.2.3 Uncertainties in demand-side mitigation potential

Both reducing ruminant meat consumption and increasing its efficiency are often identified as the main options to reduce GHG emissions (GHGE) and to lessen pressure on land (Westhoek et al. 2014) (see Section 5.6 for synergies and trade-offs with health and Section 5.7 for discussion of Just Transitions). However, analysing ruminant meat production is highly complex because of the extreme heterogeneity of production systems and due to the numerous products and services associated with ruminants (Gerber et al. 2015). See Supplementary Material Section SM5.5 for further discussion of uncertainties in estimates of livestock mitigation technical potential. Further, current market mechanisms are regarded as insufficient to decrease consumption or increase efficiency, and governmental intervention is often suggested to encourage mitigation in both the supply-side and demand-side of the food system (Section 5.7) (Wirsenius et al. 2011; Henderson et al. 2018).

Minimising GHG emissions through mathematical programming with near-minimal acceptability constraints can be understood as a reference or technical potential for mitigation through diet shifts. In this context (Macdiarmid et al. 2012) found up to 36% reduction in emissions in UK with similar diet costs applying fixed lifecycle analyses (LCA) carbon footprints (i.e., no rebound effects considered). Westhoek et al. (2014) found 25–40% in emissions by halving meat, dairy and egg intake in the EU, applying standard IPCC fixed emission intensity factors. Uncertainty about the consequences of on-the-ground implementation of policies towards low ruminant meat consumption in the food system and their externalities remain noteworthy.

Often, all emissions are allocated only to human edible meat and the boundaries are set only within the farm gate (Henderson et al. 2018; Gerber et al. 2013). However, less than 50% of slaughtered cattle weight is human edible meat, and 1–10% of the mass is lost or incinerated, depending on specified risk materials legislation. The remaining mass provide inputs to multiple industries, for example clothing, furniture, vehicle coating materials, biofuel, gelatine, soap, cosmetics, chemical and pharmaceutical industrial supplies, pet feed ingredients and fertilisers (Marti et al. 2011; Mogensen et al. 2016; Sousa et al. 2017). This makes ruminant meat production one of the most complex problems for LCA in the food system (Place and Mitloehner 2012; de Boer et al. 2011). There are only a few examples taking into account slaughter by-products (Mogensen et al. 2016).

5.5.2.4 Insect-based diets

Edible insects are, in general, rich in protein, fat, and energy and can be a significant source of vitamins and minerals (Rumpold and Schlüter 2015). Approximately 1900 insect species are eaten worldwide, mainly in developing countries (van Huis 2013). The development of safe rearing and effective processing methods are mandatory for utilisation of insects in food and feed. Some insect species can be grown on organic side streams, reducing environmental contamination and transforming waste into high-protein feed. Insects are principally considered as meat substitutes, but worldwide meat substitute consumption is still very low, principally due to differences in food culture, and will require transition phases such as powdered forms (Megido et al. 2016 and Smetana et al. 2015). Wider consumer acceptability will relate to pricing, perceived environmental benefits, and the development of tasty insect-derived protein products (van Huis et al. 2015; van Huis 2013). Clearly, increasing the share of insect-derived protein has the potential to reduce GHG emissions otherwise associated with livestock production. However, no study to date has quantified such potential.

5.5.2.5 Food loss and waste, food security, and land use

Food loss and waste impacts food security by reducing global and local food availability, limiting food access due to an increase in food prices and a decrease of producer income, affecting future food production due to the unstainable use of natural resources (HLPE 2014). Food loss is defined as the reduction of edible food during production, postharvest, and processing, whereas food discarded by consumers is considered as food waste (FAO 2011b). Combined food loss and waste amount to 25–30% of total food produced (*medium confidence*). During 2010–2016, global food loss and waste equalled 8–10% of total GHG emissions (*medium confidence*); and cost about 1 trillion USD per year (*low confidence*) (FAO 2014b).

A large share of produced food is lost in developing countries due to poor infrastructure, while a large share of produced food is wasted in developed countries (Godfray et al. 2010). Changing consumer behaviour to reduce per capita over-consumption offers substantial potential to improve food security by avoiding related health burdens (Alexander et al. 2017; Smith 2013) and reduce emissions associated with the extra food (Godfray et al. 2010). In 2007, around 20% of the food produced went to waste in Europe and North America, while around 30% of the food produced was lost in Sub-Saharan Africa (FAO 2011b). During the last 50 years, the global food loss and waste increased from around 540 Mt in 1961 to 1630 Mt in 2011 (Porter et al. 2016).

In 2011, food loss and waste resulted in about 8–10% of total anthropogenic GHG emissions. The mitigation potential of reduced food loss and waste from a full life-cycle perspective, for example, considering both food supply chain activities and land-use change, was estimated as 4.4 $GtCO_2$-eq yr^{-1} (FAO 2015a, 2013b). At a global scale, loss and waste of milk, poultry meat, pig meat, sheep meat, and potatoes are associated with 3% of the global agricultural N_2O emissions (more than 200 Gg N_2O-N yr^{-1} or 0.06 $GtCO_2$-eq yr^{-1}) in 2009 (Reay et al. 2012). For the USA, 35% of energy use, 34% of blue water use, 34% of GHG emissions, 31% of land use, and 35% of fertiliser use related to an individual's food-related resource consumption were accounted for as food waste and loss in 2010 (Birney et al. 2017).

Similar to food waste, over-consumption (defined as food consumption in excess of nutrient requirements), leads to GHG emissions (Alexander et al. 2017). In Australia for example, over-consumption accounts for about 33% GHGs associated with food (Hadjikakou 2017). In addition to GHG emissions, over-consumption can also lead to severe health conditions such as obesity or diabetes. Over-eating was found to be at least as large a contributor to food system losses (Alexander et al. 2017). Similarly, food system losses associated with consuming resource-intensive animal-based products instead of nutritionally comparable plant-based alternatives are defined as 'opportunity food losses'. These were estimated to be 96, 90, 75, 50, and 40% for beef, pork, dairy, poultry, and eggs, respectively, in the USA (Shepon et al. 2018).

Avoiding food loss and waste will contribute to reducing emissions from the agriculture sector. By 2050, agricultural GHG emissions associated with production of food that might be wasted may increase to 1.9–2.5 $GtCO_2$-eq yr^{-1} (Hiç et al. 2016). When land-use change for agriculture expansion is also considered, halving food loss and waste reduces the global need for cropland area by around 14% and GHG emissions from agriculture and land-use change by 22–28% (4.5 $GtCO_2$-eq yr^{-1}) compared to the baseline scenarios by 2050 (Bajželj et al. 2014). The GHG emissions mitigation potential of food loss and waste reduction would further increase when lifecycle analysis accounts for emissions throughout food loss and waste through all food system activities.

Reducing food loss and waste to zero might not be feasible. Therefore, appropriate options for the prevention and management of food waste can be deployed to reduce food loss and waste and to minimise its environmental consequences. Papargyropoulou et al. (2014) proposed the Three Rs (i.e., reduction, recovery and recycle) options to prevent and manage food loss and waste. A wide range of approaches across the food supply chain is available to reduce food loss and waste, consisting of technical and non-technical solutions (Lipinski et al. 2013). However, technical solutions (e.g., improved harvesting techniques, on-farm storage, infrastructure, packaging to keep food fresher for longer, etc.) include additional costs (Rosegrant et al. 2015) and may have impacts on local environments (FAO 2018b). Additionally, all parts of food supply chains need to become efficient to achieve the full reduction potential of food loss and waste (Lipinski et al. 2013).

Together with technical solutions, approaches (i.e., non-technical solutions) to changes in behaviours and attitudes of a wide range of stakeholders across the food system will play an important role in reducing food loss and waste. Food loss and waste can be recovered by distributing food surplus to groups affected by food poverty or converting food waste to animal feed (Vandermeersch et al. 2014). Unavoidable food waste can also be recycled to produce energy based on biological, thermal and thermochemical technologies (Pham et al. 2015). Additionally, strategies for reducing food loss and waste also need to consider gender dynamics with participation of females throughout the food supply chain (FAO 2018f).

In summary, reduction of food loss and waste can be considered as a climate change mitigation measure that provides synergies with food security and land use (*robust evidence*, *medium agreement*). Reducing food loss and waste reduces agricultural GHG emissions and the need for agricultural expansion for producing excess food. Technical options for reduction of food loss and waste include improved harvesting techniques, on-farm storage, infrastructure, and packaging. However, the beneficial effects of reducing food loss and waste will vary between producers and consumers, and across regions. Causes of food loss (e.g., lack of refrigeration) and waste (e.g., behaviour) differ substantially in developed and developing countries (*robust evidence*, *medium agreement*). Additionally, food loss and waste cannot be avoided completely.

5.5.2.6 Shortening supply chains

Encouraging consumption of locally produced food and enhancing efficiency of food processing and transportation can, in some cases, minimise food loss, contribute to food security, and reduce GHG emissions associated with energy consumption and food loss. For example, Michalský and Hooda (2015), through a quantitative assessment of GHG emissions of selected fruits and vegetables in the UK, reported that increased local production offers considerable emissions savings. They also highlighted that when imports are necessary, importing from Europe instead of the Global South can contribute to considerable GHG emissions savings. Similar results were found by Audsley et al. (2010), with exceptions for some foods, such as tomatoes, peppers or sheep and goat meat. Similarly, a study in India shows that long and fragmented supply chains, which lead to disrupted price signals, unequal power relations perverse incentives and long transport time, could be a key barrier to reducing post-harvest losses (CIPHET 2007).

In other cases, environmental benefits associated with local food can be offset by inefficient production systems with high emission intensity and resource needs, such as water, due to local conditions. For example, vegetables produced in open fields can have much lower GHG emissions than locally produced vegetables from heated greenhouses (Theurl et al. 2014). Whether locally grown food has a lower carbon footprint depends on the on-farm emissions intensity as well as the transport emissions. In some cases, imported food may have a lower carbon footprint than locally grown food because some distant countries can produce food at much lower emissions intensity. For example, Avetisyan et al. (2014) reported that regional variation of emission intensities associated with production of ruminant products have large implications for emissions associated with local food. They showed that consumption of local livestock products can reduce emissions due to short supply chains in countries with low emission intensities; however, this might not be the case in countries with high emission intensities.

In addition to improving emission intensity, efficient distribution systems for local food are needed for lowering carbon footprints (Newman et al. 2013). Emissions associated with food transport depend on the mode of transport, for example, emissions are lower for rail rather than truck (Brodt et al. 2013). Tobarra et al. (2018) reported that emissions saving from local food may vary across seasons and regions of import. They highlighted that, in Spain, local production of fruits and vegetables can reduce emissions associated with imports from Africa but imports from France and Portugal can save emissions in comparison to production in Spain. Additionally, local production of seasonal products in Spain reduces emissions, while imports of out-of-season products can save emissions rather than producing them locally.

In summary, consuming locally grown foods can reduce GHG emissions, if they are grown efficiently (*high confidence*). The emissions reduction potential varies by region and season. Whether food with shorter supply chains has a lower carbon footprint depends on both the on-farm emissions intensity as well as the transport emissions. In some cases, imported food may have a lower carbon footprint because some distant agricultural regions can produce food at lower emissions intensities.

5.6 Mitigation, adaptation, food security and land use: Synergies, trade-offs and co-benefits

Food systems will need to adapt to changing climates and also reduce their GHG emissions and sequester carbon if Paris Agreement goals are to be met (Springmann et al. 2018a and van Vuuren et al. 2014). The synergies and trade-offs between the food system mitigation and adaptation options described in Sections 5.3 and 5.5 are of increasing importance in both scientific and policy communities because of the necessity to ensure food security, i.e., providing nutritious food for growing populations while responding to climate change (Rosenzweig and Hillel 2015). A special challenge involves interactions between land-based non-food system mitigation, such as negative emissions technologies, and food security. Response options for the food system have synergies and trade-offs between climate change mitigation and adaptation (Figure 5.13; Chapter 6).

Tirado et al. (2013) suggest an integrated approach to address the impacts of climate change to food security that considers a combination of nutrition-sensitive adaptation and mitigation measures, climate-resilient and nutrition-sensitive agricultural development, social protection, improved maternal and child care and health, nutrition-sensitive risk reduction and management, community development measures, nutrition-smart investments, increased policy coherence, and institutional and cross-sectoral collaboration. These measures are a means to achieve both short-term and long-term benefits in poor and marginalised groups.

This section assesses the synergies and trade-offs for land-based atmospheric carbon dioxide removal measures, effects of mitigation measures on food prices, and links between dietary choices and human health. It then evaluates a range of integrated agricultural systems and practices that combine mitigation and adaptation measures, including the role of agricultural intensification. The role urban agriculture is examined, as well as interactions between SDG 2 (zero hunger) and SDG 13 (climate action).

5.6.1 Land-based carbon dioxide removal (CDR) and bioenergy

Large-scale deployment of negative emission technologies (NETs) in emission scenarios has been identified as necessary for avoiding unacceptable climate change (IPCC 2018b). Among the available NETs, carbon dioxide removal (CDR) technologies are receiving increasing attention. Land-based CDRs include afforestation and reforestation (AR), sustainable forest management, biomass energy with carbon capture and storage (BECCS), and biochar (BC) production (Minx et al. 2018). Most of the literature on global land-based mitigation potential relies on CDRs, particularly on BECCS, as a major mitigation action (Kraxner et al. 2014; Larkin et al. 2018 and Rogelj et al. 2018, 2015, 2011). BECCS is not yet deployable at a significant scale, as it faces challenges similar to fossil fuel carbon capture and storage (CCS) (Fuss et al. 2016; Vaughan and Gough 2016; Nemet et al. 2018). Regardless, the effectiveness of large-scale BECCS to meet Paris Agreement goals has been questioned and other pathways to mitigation have been proposed (Anderson and Peters 2016; van Vuuren et al. 2017, 2018; Grubler et al. 2018; Vaughan and Gough 2016).

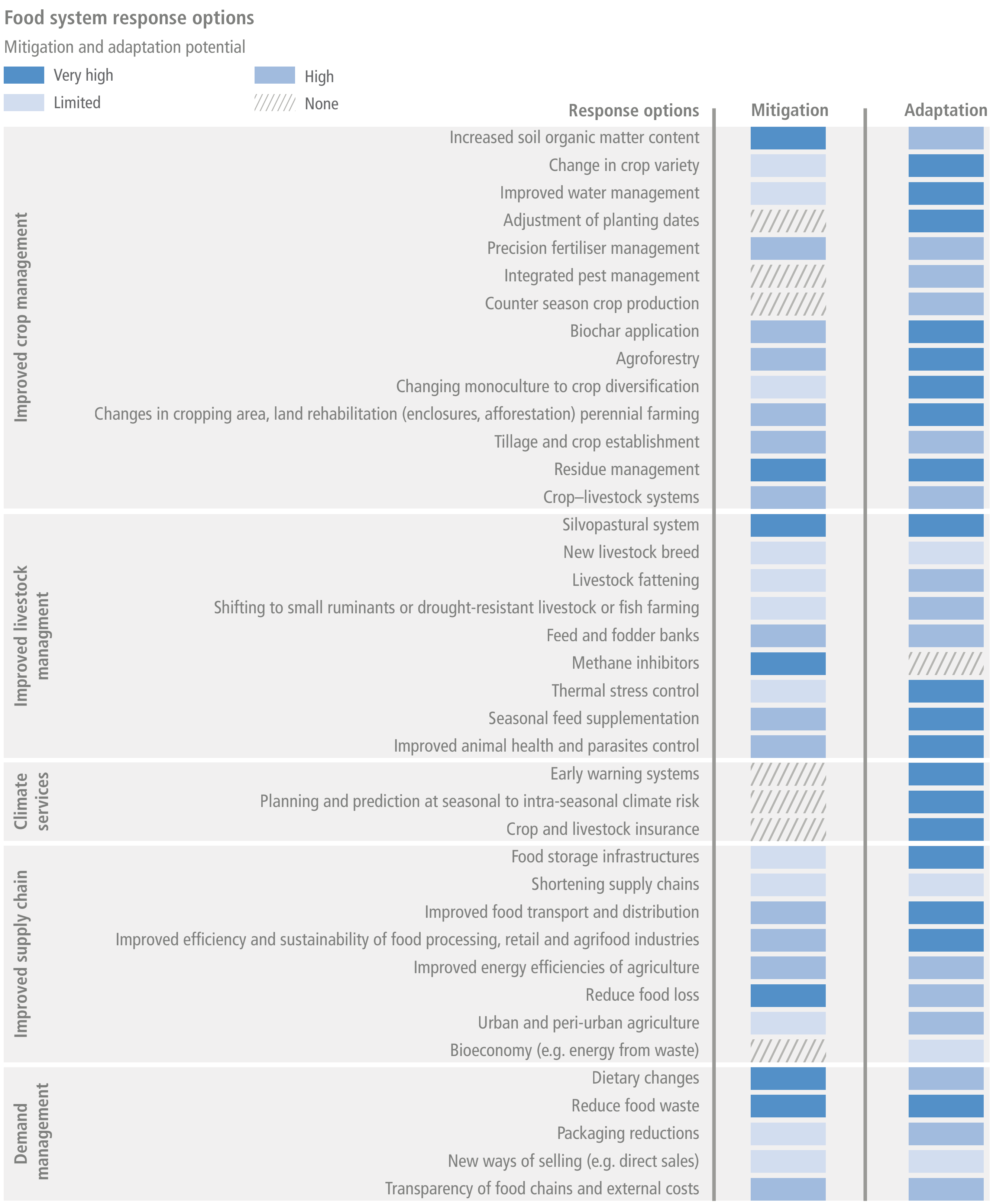
Atmospheric CO_2 removal by storage in vegetation depends on achieving net organic carbon accumulation in plant biomass over decadal time scales (Kemper 2015) and, after plant tissue decay, in soil organic matter (Del Grosso et al. 2019). AR, BECCS and BC differ in the use and storage of plant biomass. In BECCS, biomass carbon from plants is used in industrial processes (e.g., for electricity, hydrogen, ethanol, and biogas generation), releasing CO_2, which is then captured and geologically stored (Greenberg et al. 2017; Minx et al. 2018).

Afforestation and reforestation result in long-term carbon storage in above and belowground plant biomass on previously unforested areas, and is effective as a carbon sink during the AR establishment period, in contrast to thousands of years for geological carbon storage (Smith et al. 2016).

Biochar is produced from controlled thermal decomposition of biomass in absence of oxygen (pyrolysis), a process that also yields combustible oil and combustible gas in different proportions. Biochar is a very stable carbon form, with storage on centennial time scales (Lehmann et al. 2006) (Chapter 4). Incorporated in soils, some authors suggest it may lead to improved water-holding capacity, nutrient retention, and microbial processes (Lehmann et al. 2015). There is, however, uncertainty about the benefits and risks of this practice (The Royal Society 2018).

Land-based CDRs require high biomass-producing crops. Since not all plant biomass is harvested (e.g., roots and harvesting losses), it can produce co-benefits related to soil carbon sequestration, crop productivity, crop quality, as well improvements in air quality, but the overall benefits strongly depend on the previous land-use and soil management practices (Smith et al. 2016; Wood et al. 2018). In addition, CDR effectiveness varies widely depending on type of biomass, crop productivity, and emissions offset in the energy system. Importantly, its mitigation benefits can be easily lost due to land-use change interactions (Harper et al. 2018; Fuss et al. 2018; Daioglou et al. 2019).

Major common challenges of implementing these large-scale CDR solutions, as needed to stabilise global temperature at 'well-below' 2°C by the end of the century, are the large investments and the associated significant changes in land use required. Most of the existing scenarios estimate the global area required for energy crops in the range of 109–990 Mha (IPCC 2018a), most commonly around 380–700 Mha (Smith et al. 2016), reaching net area expansion rates of up to 23.7 Mha yr^{-1} (IPCC 2018b). The upper limit implies unprecedented rates of area expansion for crops and forestry observed historically, for instance, as reported by FAO since 1961 (FAOSTAT 2018). By comparison, the sum of recent worldwide rates of expansion in the harvested area of soybean and sugarcane has not exceeded 3.5 Mha yr^{-1} on average. Even at this rate, they have been the source of major concerns for their possible negative environmental and food security impacts (Boerema et al. 2016; Popp et al. 2014).



Food system response options

Mitigation and adaptation potential

■ Very high
▣ High
□ Limited
▨ None

	Response options	Mitigation	Adaptation
Improved crop management	Increased soil organic matter content	■	▣
	Change in crop variety	□	■
	Improved water management	□	■
	Adjustment of planting dates	▨	■
	Precision fertiliser management	▣	▣
	Integrated pest management	▨	▣
	Counter season crop production	▨	▣
	Biochar application	▣	■
	Agroforestry	▣	■
	Changing monoculture to crop diversification	□	■
	Changes in cropping area, land rehabilitation (enclosures, afforestation) perennial farming	▣	■
	Tillage and crop establishment	▣	▣
	Residue management	■	■
	Crop–livestock systems	▣	▣
Improved livestock managment	Silvopastural system	■	■
	New livestock breed	□	□
	Livestock fattening	□	▣
	Shifting to small ruminants or drought-resistant livestock or fish farming	□	▣
	Feed and fodder banks	▣	▣
	Methane inhibitors	■	▨
	Thermal stress control	□	■
	Seasonal feed supplementation	▣	■
	Improved animal health and parasites control	▣	■
Climate services	Early warning systems	▨	■
	Planning and prediction at seasonal to intra-seasonal climate risk	▨	■
	Crop and livestock insurance	▨	■
Improved supply chain	Food storage infrastructures	□	■
	Shortening supply chains	□	□
	Improved food transport and distribution	▣	■
	Improved efficiency and sustainability of food processing, retail and agrifood industries	▣	■
	Improved energy efficiencies of agriculture	▣	▣
	Reduce food loss	■	▣
	Urban and peri-urban agriculture	□	▣
	Bioeconomy (e.g. energy from waste)	▨	□
Demand management	Dietary changes	■	▣
	Reduce food waste	■	■
	Packaging reductions	□	▣
	New ways of selling (e.g. direct sales)	□	□
	Transparency of food chains and external costs	▣	▣

Figure 5.13 | Response options related to food system and their potential impacts on mitigation and adaptation. Many response options offer significant potential for both mitigation and adaptation.

Most land area available for CDR is currently pasture, estimated at 3300 Mha globally (FAOSTAT 2018). However, there is *low confidence* about how much low-productivity land is actually available for CDR (Lambin et al. 2013 and Gibbs and Salmon 2015). There is also *low confidence* as to whether the transition to BECCS will take place directly on low-productivity grasslands (Johansson and Azar 2007), and uncertainty on the governance mechanisms required to avoid unwanted spill-over effects, for instance causing additional deforestation (Keles et al. 2018).

Further, grasslands and rangelands may often occur in marginal areas, in which case, they may be exposed to climate risks, including periodic flooding. Grasslands and especially rangelands and savannas tend to predominate in less-developed regions, often bordering areas of natural vegetation with little infrastructure available for transport and processing of large quantities of CDR-generated biomass (O'Mara 2012; Beringer et al. 2011; Haberl et al. 2010; Magdoff 2007).

CDR-driven reductions in the available pastureland area is a scenario of constant or increasing global animal protein output as proposed by Searchinger et al. (2018). However, despite the recent reduction in meat consumption in western countries, this will require productivity improvements (Cohn et al. 2014; Strassburg et al. 2014). It would also result in lower emission intensities and create conditions for increased soil carbon stocks (de Oliveira Silva et al. 2016; Searchinger et al. 2018; Soussana et al. 2019, 2013). At the same time, food security may be threatened if land-based mitigation displaced crops elsewhere, especially if to regions of lower productivity potential, higher climatic risk, and higher vulnerability.

There is *low agreement* about what are the more competitive regions of the world for CDRs. Smith et al. (2016) and Vaughan et al. (2018) identify as candidates relatively poor countries in Latin America, Africa and Asia (except China and India). Others indicate those regions may be more competitive for food production, placing Europe as a major BECCS exporter (Muratori et al. 2016). Economically feasible CDR investments are forecast to be directed to regions with high biomass production potential, demand for extra energy production, low leakage potential for deforestation and low competition for food production (Vaughan et al. 2018). Latin America and Africa, for instance, although having high biomass production potential, still have low domestic energy consumption (589 and 673 MTOE – 24.7 and 28.2 EJ, respectively), with about 30% of primary energy from renewable sources (reaching 50% in Brazil), mainly hydropower and traditional biomass.

There is *high confidence* that deployment of BECCS will require ambitious investments and policy interventions (Peters and Geden 2017) with strong regulation and governance of bioenergy production to ensure protection of forests, maintain food security and enhance climate benefits (Burns and Nicholson 2017; Vaughan et al. 2018; Muratori et al. 2016), and that such conditions may be challenging for developing countries. Increased value of bioenergy puts pressure on land, ecosystem services, and the prices of agricultural commodities, including food (*high confidence*).

There is *medium confidence* for the impact of CDR technologies on increased food prices and reduced food security, as these depend on several assumptions. Nevertheless, those impacts could be strong, with food prices doubling under certain scenario combinations (Popp et al. 2017). The impacts of land-mitigation policies on the reduction of dietary energy availability alone (without climate change impacts) is estimated at over 100 kcal per person per day by 2050, with highest regional impacts in South Asia and Sub-Saharan Africa (Hasegawa et al. 2018) (Section 5.2). However, only limited pilot BECCS projects have been implemented to date (Lenzi et al. 2018). Integrated assessment models (IAMs) use theoretical data based on high-level studies and limited regional data from the few on-the-ground BECCS projects.

Furthermore, it has been suggested that several BECCS IAM scenarios rely on unrealistic assumptions regarding regional climate, soils and infrastructure suitability (Anderson and Peters 2016), as well as international bioenergy trade (Lamers et al. 2011). Current global IAMs usually consider major trends in production potential and projected demand, overlooking major challenges for the development of a reliable international market. Such a market will have to be created from scratch and overcome a series of constraints, including trade barriers, logistics, and supply chains, as well as social, ecological and economic impacts (Matzenberger et al. 2015).

In summary, there is *high agreement* that better assessment of BECCS mitigation potential would need to be based on increased regional, bottom-up studies of biomass potentials, socio-economic consequences (including on food security), and environmental impacts in order to develop more realistic estimates (IPCC 2018a).

5.6.2 Mitigation, food prices, and food security

Food prices are the result of supply, demand and trade relations. Earlier studies (e.g., Nelson et al. 2009) showed that recent climate impacts that reduced crop productivity led to higher prices and increased trade of commodities between regions, with asymmetric impacts on producers and consumers. In terms of published scenario analyses, the most affected regions tend to be Sub-Saharan Africa and parts of Asia, but there is significant heterogeneity in results between countries. Relocation of production to less affected areas buffers these impacts to a certain extent, and offers potential for improvements in food production technologies (Hasegawa et al. 2018; van Meijl et al. 2017; Wiebe et al. 2015; Lotze-Campen et al. 2014; Valin et al. 2014; Robinson et al. 2014).

A newer, less studied impact of climate change on prices and their impacts on food security is the level of land-based mitigation necessary to stabilise global temperature. Hasegawa et al. (2018), using an ensemble of seven global economic models across a range of GHG emissions pathways and socioeconomic trajectories, suggested that the level of mitigation effort needed to reduce emissions can have a more significant impact on prices than the climate impacts themselves on reduced crop yields (Figure 5.14). This occurs because in the models, taxing GHG emissions leads to higher crop and livestock prices, while land-based mitigation leads to less

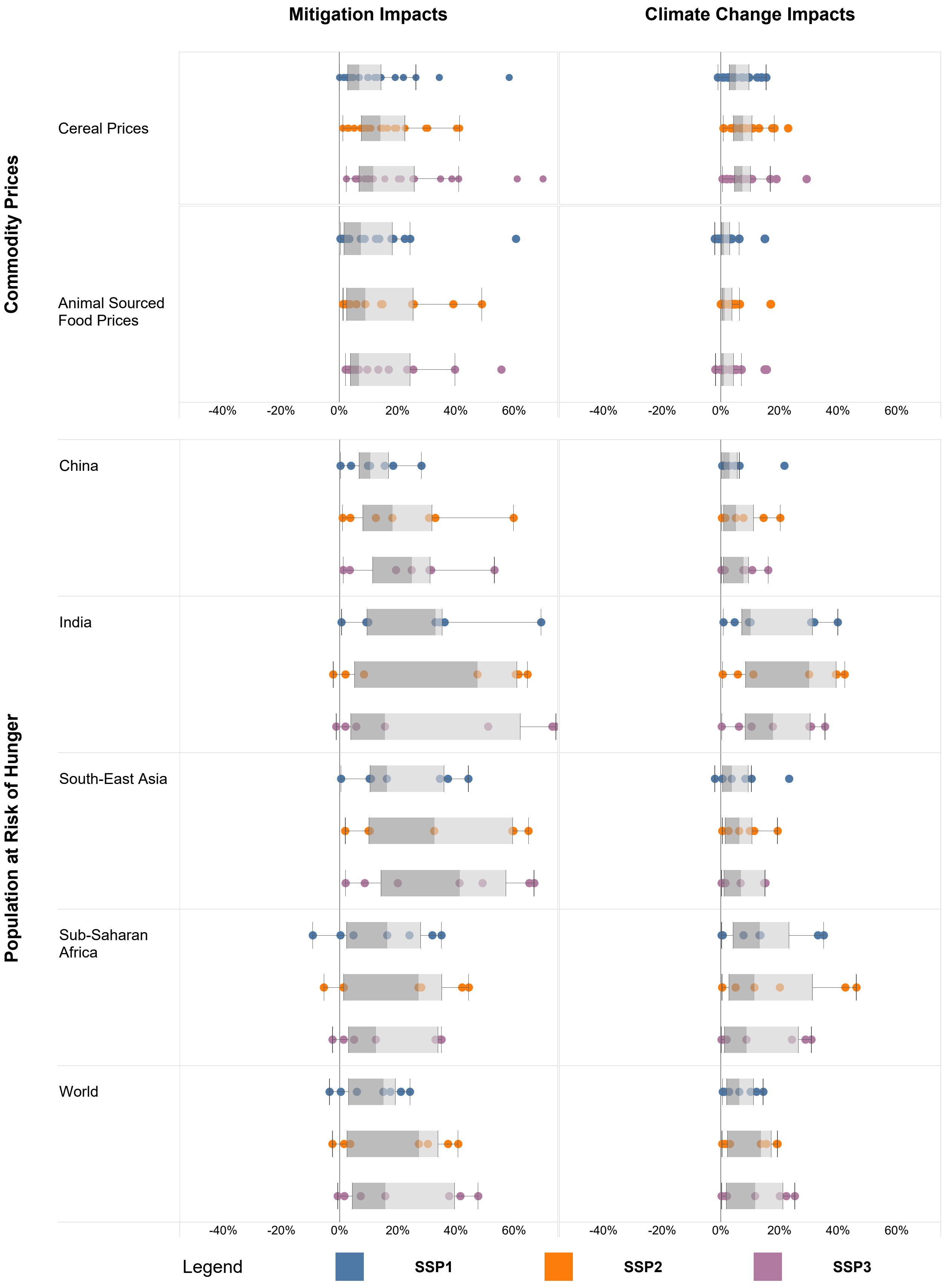


Figure 5.14 | Regional impacts of climate change and mitigation on food price (top), population at risk of hunger or undernourishment (middle), GHG emissions (bottom) in 2050 under different socio-economic scenarios (SSP1, SSP2 and SSP3) based on AgMIP Global Economic Model analysis. Values indicate changes from no climate change and no climate change mitigation scenario. MAgPIE, a global land-use allocation model, is excluded due to inelastic food demand. The value of India includes that of Other Asia in MAGNET, a global general equilibrium model (Hasegawa et al. 2018).

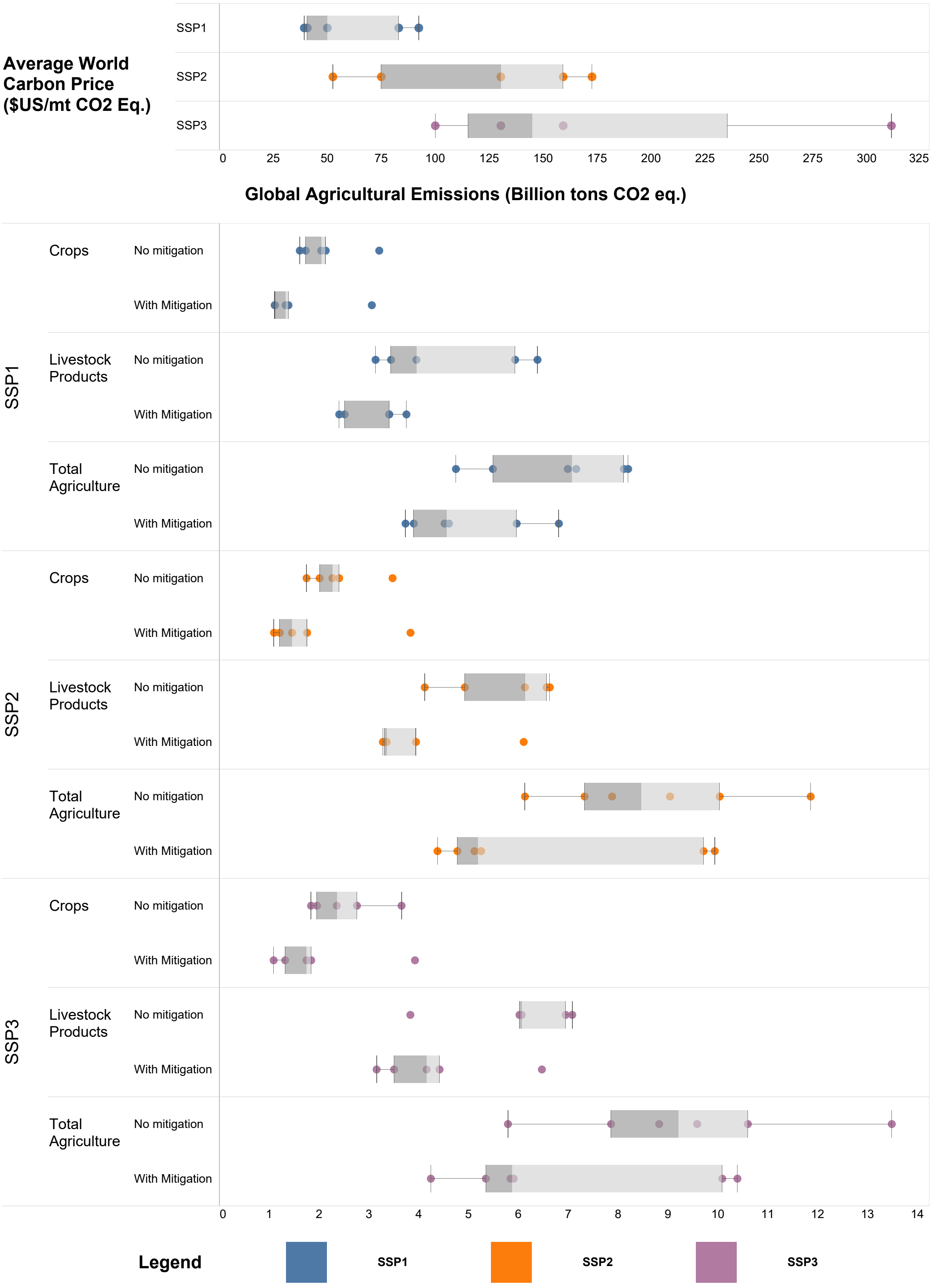


Figure 5.14 (continued).

land availability for food production, potentially lower food supply, and therefore food price increases.

Price increases in turn lead to reduced consumption, especially by vulnerable groups, or to shifts towards cheaper food, which are often less nutritious. This leads to significant increases in the number of malnourished people. Frank et al. (2017) and Fujimori et al. (2017) arrived at the same conclusions for the 1.5°C mitigation scenario using the IAM Globiom and ensembles of AgMIP global economic models. While the magnitude of the response differs between models, the results are consistent between them. In contrast, a study based on five global agroeconomic models highlights that the global food prices may not increase much when the required land for bioenergy is accessible on the margin of current cropland, or the feedstock does not have a direct completion with agricultural land (Lotze-Campen et al. 2014).

These studies highlight the need for careful design of emissions mitigation policies in upcoming decades – for example, targeted schemes encouraging more productive and resilient agricultural production systems and the importance of incorporating complementary policies (such as safety-net programmes for poverty alleviation) that compensate or counteract the impacts of climate change mitigation policies on vulnerable regions (Hasegawa et al. 2018). Fujimori et al. (2018) showed how an inclusive policy design can avoid adverse side effects on food security through international aid, bioenergy taxes, or domestic reallocation of income. These strategies can shield impoverished and vulnerable people from the additional risk of hunger that would be caused by the economic effects of policies narrowly focussing on climate objectives only.

In summary, food security will be threatened through increasing numbers of malnourished people if land-based mitigation raises prices, unless other policy mechanisms reduce its impact (*high confidence*). Inclusive policy design can avoid adverse side effects on food security by shielding vulnerable people from the additional risk of hunger that would be caused by the economic effects of policies narrowly focusing on climate objectives (*medium confidence*).

5.6.3 Environmental and health effects of adopting healthy and sustainable diets

Two key questions arise from the potentially significant mitigation potential of dietary change: (i) Are 'low-GHG emission diets' likely to be beneficial for health? and (ii) Would changing diets at scale provide substantial benefits? In short, what are the likely synergies and trade-offs between low-GHG emissions diets and food security, health, and climate change? See Supplementary Material Section SM5.6 for further discussion.

Are 'low GHG emission diets' healthy? Consistent evidence indicates that, in general, a dietary pattern that is higher in plant-based foods, such as vegetables, fruits, whole grains, legumes, nuts, and seeds, and lower in animal-based foods, is more health-promoting and associated with lower environmental impact (GHG emissions and energy, land and water use) than either the current global average diets (Swinburn et al. 2019; Willett et al. 2019; Springmann et al. 2016b), or the current average USA diet (Nelson et al. 2016). Another study (Van Mierlo et al. 2017) showed that nutritionally-equivalent diets can substitute plant-based foods for meat and provide reductions in GHG emissions.

There are several studies that estimate health adequacy and sustainability and conclude that healthy sustainable diets are possible. These include global studies (e.g., Willett et al. 2019; Swinburn et al. 2019), as well as localised studies (e.g., Van Dooren et al. 2014). For example, halving consumption of meat, dairy products and eggs in the European Union would achieve a 40% reduction in ammonia emissions, 25–40% reduction in non-CO_2 GHG emissions (primarily from agriculture) and 23% per capita less use of cropland for food production, with dietary changes lowering health risks (Westhoek et al. 2014). In China, diets were designed that could meet dietary guidelines while creating significant reductions in GHG emissions (between 5% and 28%, depending on scenario) (Song et al. 2017). Changing diets can also reduce non-dietary related health issues caused by emissions of air pollutants. For example, specific changes in diets were assessed for their potential to mitigate PM 2.5 in China (Zhao et al. 2017b).

Some studies are starting to estimate both health and environmental benefits from dietary shifts. For example, Farchi et al. (2017) estimate health (colorectal cancer, cardiovascular disease) and GHG outcomes of 'Mediterranean' diets in Italy, and found the potential to reduce deaths from colorectal cancer of 7–10% and CVD from 9–10%, as well as potential savings of up to 263 CO_2-eq per person per year. In the USA, Hallström et al. (2017) found that adoption of healthier diets (consistent with dietary guidelines, and reducing amounts of red and processed meats) could reduce relative risk of coronary heart disease, colorectal cancer, and type 2 diabetes by 20–45%, USA healthcare costs by 77–93 billion USD per year, and direct GHG emissions by 222–826 kg CO_2-eq per person per year (69–84 kg from the healthcare system, 153–742 kg from the food system). Broadly similar conclusions were found for the Netherlands (Biesbroek et al. 2014); and the UK (Friel et al. 2009 and Milner et al. 2015).

Whilst for any given disease, there are a range of factors, including diet, that can affect it, and evidence is stronger for some diseases than others, a recent review found that an overall trend toward increased cancer risk was associated with unhealthy dietary patterns, suggesting that diet-related choices could significantly affect the risk of cancer (Grosso et al. 2017). Tilman and Clark (2014) found significant benefits in terms of reductions in relative risk of key diseases: type 2 diabetes, cancer, coronary mortality and all causes of mortality (Figure 5.15).

5.6.3.1 Can dietary shifts provide significant benefits?

Many studies now indicate that dietary shifts can significantly reduce GHG emissions. For instance, several studies highlight that if current dietary trends are maintained, this could lead to emissions from agriculture of approximately 20 $GtCO_2$-eq yr^{-1} by 2050, creating significant mitigation potential (Pradhan et al. 2013b; Bajželj et al. 2014; Hedenus et al. 2014; Bryngelsson et al. 2017). Additionally in

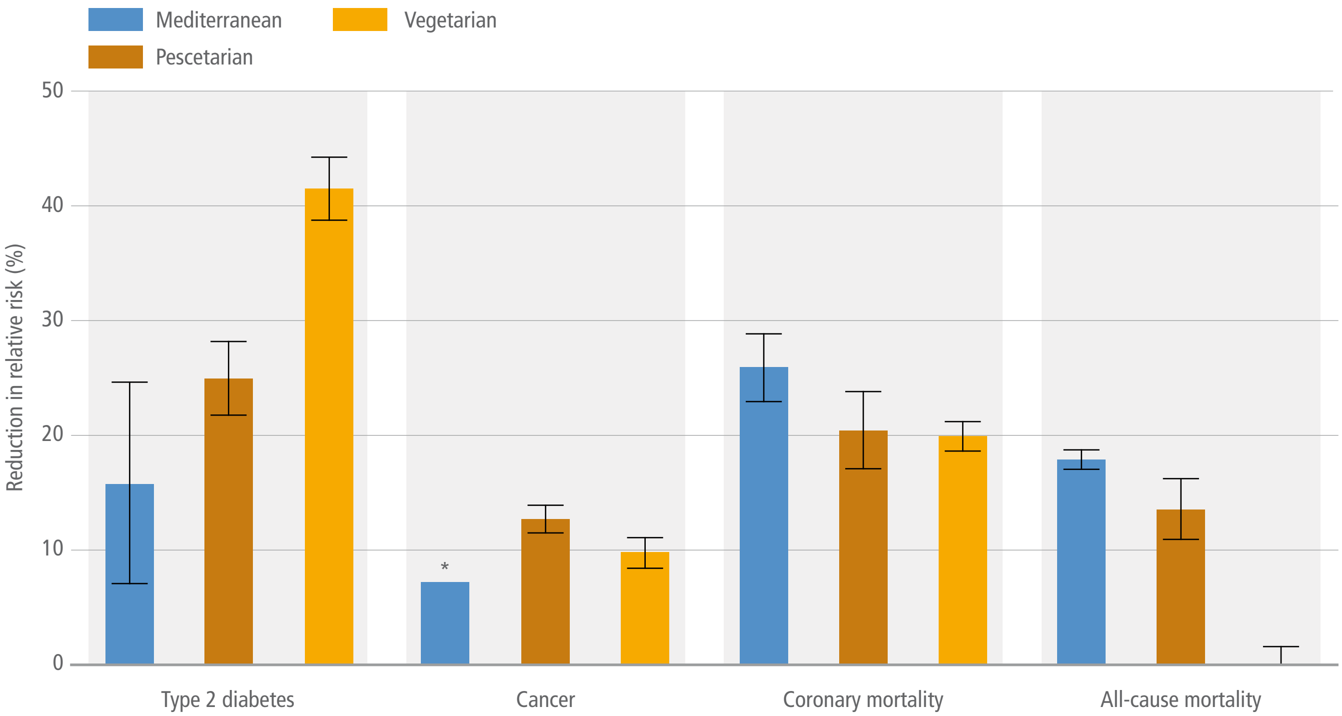


Figure 5.15 | Diet and health effects of different consumption scenarios (Tilman and Clark 2014) (*reflects data from a single study, hence no error bars).

the USA, a shift in consumption towards a broadly healthier diet, combined with meeting the USDA and Environmental Protection Agency's 2030 food loss and waste reduction goals, could increase *per capita* food-related energy use by 12%, decrease blue water consumption by 4%, decrease green water use by 23%, decrease GHG emissions from food production by 11%, decrease GHG emissions from landfills by 20%, decrease land use by 32%, and increase fertiliser use by 12% (Birney et al. 2017). This study, however, does not account for all potential routes to emissions, ignoring, for example, fertiliser use in feed production. Similar studies have been conducted, for China (Li et al. 2016), where adoption of healthier diets and technology improvements have the potential to reduce food systems GHG emissions by >40% relative to those in 2010; and India (Green et al. 2017; Vetter et al. 2017), where alternative diet scenarios can affect emissions from the food system by –20 to +15%.

Springmann et al.(2018a) modelled the role of technology, waste reduction and dietary change in living within planetary boundaries (Rockström et al. 2009), with the climate change boundary being a 66% chance of limiting warming to less than 2°C. They found that all are necessary for the achievement of a sustainable food system. Their principal conclusion is that only by adopting a 'flexitarian diet', as a global average, would climate change be limited to under two degrees. Their definition of a flexitarian diet is fruits and vegetables, plant-based proteins, modest amounts of animal-based proteins, and limited amounts of red meat, refined sugar, saturated fats, and starchy foods.

Healthy and sustainable diets address both health and environmental concerns (Springmann et al. 2018b). There is high agreement that there are significant opportunities to achieve both objectives simultaneously. Contrasting results of marginal GHG emissions, that is, variations in emissions as a result of variation in one or more dietary components, are found when comparing low to high emissions in self-selected diets (diets freely chosen by consumers). Vieux et al. (2013) found self-selected healthier diets with higher amounts of plant-based food products did not result in lower emissions, while (Rose et al. 2019) found that the lowest emission diets analysed were lower in meat but higher in oil, refined grains and added sugar. Vieux et al. (2018) concluded that setting nutritional goals with no consideration for the environment may increase GHG emissions.

Tukker et al. (2011) also found a slight increase in emissions by shifting diets towards the European dietary guidelines, even with lower meat consumption. Heller and Keoleian (2015) found a 12% increase in GHG emissons when shifting to iso-caloric diets, defined as diets with the same caloric intake of diets currently consumed, following the USA guidelines and a 1% decrease in GHG emissions when adjusting caloric intake to recommended levels for moderate activity. There is scarce information on the marginal GHG emissions that would be associated with following dietary guidelines in developing countries.

Some studies have found a modest mitigation potential of diet shifts when economic and biophysical systems effects are taken into account in association with current dietary guidelines. Tukker et al. (2011), considering economic rebound effects of diet shifts (i.e., part of the gains would be lost due to increased use at lower prices), found maximum changes in emissions of the EU food system of 8% (less than 2% of total EU emissions) when reducing meat consumption by 40 to 58%. Using an economic optimisation model for studying carbon taxation in food but with adjustments of agricultural production systems and commodity markets in Europe, Zech and Schneider (2019) found a reduction of 0.41% in GHG emissions at a tax level of 50 USD per tCO_2-eq. They estimate a leakage of 43% of the GHG emissions reduced by domestic consumption, (i.e., although reducing emissions due to reducing consumption, around 43% of the emissions would not be reduced because part of the production would be directed to exports).

Studying optimised beef production systems intensification technologies in a scenario of no grasslands area expansion de Oliveira Silva et al. (2016) found marginal GHG emissions to be negligible in response to beef demand in the Brazilian Cerrado. This was because reducing productivity would lead to increased emission intensities, cancelling out the effect of reduced consumption.

In summary, there is significant potential mitigation (*high confidence*) arising from the adoption of diets in line with dietary recommendations made on the basis of health. These are broadly similar across most countries. These are typically capped at the number of calories and higher in plant-based foods, such as vegetables, fruits, whole grains, legumes, nuts and seeds, and lower in animal-sourced foods, fats and sugar. Such diets have the potential to be both more sustainable and healthier than alternative diets (but healthy diets are not necessarily sustainable and vice versa). The extent to which the mitigation potential of dietary choices can be realised requires both climate change and health being considered together. Socio-economic (prices, rebound effects), political, and cultural contexts would require significant consideration to enable this mitigation potential to be realised.

5.6.4 Sustainable integrated agricultural systems

A range of integrated agricultural systems are being tested to evaluate synergies between mitigation and adaptation and lead to low-carbon and climate-resilient pathways for sustainable food security and ecosystem health (*robust evidence, medium agreement*). Integration refers to the use of practices that enhance an agroecosystem's mitigation, resilience, and sustainability functions. These systems follow holistic approaches with the objective of achieving biophysical, socio-cultural, and economic benefits from land management systems (Sanz et al. 2017). These integrated systems may include agroecology (FAO et al. 2018; Altieri et al. 2015), climate smart agriculture (FAO 2011c; Lipper et al. 2014; Aggarwal et al. 2018), conservation agriculture (Aryal et al. 2016; Sapkota et al. 2015), and sustainable intensification (FAO 2011d; Godfray 2015), amongst others.

Many of these systems are complementary in some of their practices, although they tend to be based on different narratives (Wezel et al. 2015; Lampkin et al. 2015; Pimbert 2015). They have been tested in various production systems around the world (Dinesh et al. 2017; Jat et al. 2016; Sapkota et al. 2015 and Neufeldt et al. 2013). Many technical innovations, for example, precision nutrient management (Sapkota et al. 2014) and precision water management (Jat et al. 2015), can lead to both adaptation and mitigation outcomes and even synergies; although negative adaptation and mitigation outcomes (i.e., trade-offs) are often overlooked. Adaptation potential of ecologically intensive systems includes crop diversification, maintaining local genetic diversity, animal integration, soil organic management, water conservation and harvesting the role of microbial assemblages (Section 5.3). Technical innovations may encompass not only inputs reduction, but complete redesign of agricultural systems (Altieri et al. 2017) and how knowledge is generated (Levidow et al. 2014), including social and political transformations.

5.6.4.1 Agroecology

Agroecology (see Glossary) (Francis et al. 2003; Gliessman and Engles 2014; Gliessman 2018), provides knowledge for their design and management, including social, economic, political, and cultural dimensions (Dumont et al. 2016). It started with a focus at the farm level but has expanded to include the range of food system activities (Benkeblia 2018). Agroecology builds systems resilience through knowledge-intensive practices relying on traditional farming systems and co-generation of new insights and information with stakeholders through participatory action research (Menéndez et al. 2013). It provides a multidimensional view of food systems within ecosystems, building on ILK and co-evolving with the experiences of local people, available natural resources, access to these resources, and ability to share and pass on knowledge among communities and generations, emphasising the inter-relatedness of all agroecosystem components and the complex dynamics of ecological processes (Vandermeer 1995).

At the farm level, agroecological practices recycle biomass and regenerate soil biotic activities. They strive to attain balance in nutrient flows to secure favourable soil and plant growth conditions, minimise loss of water and nutrients, and improve use of solar radiation. Practices include efficient microclimate management, soil cover, appropriate planting time and genetic diversity. They seek to promote ecological processes and services such as nutrient cycling, balanced predator/prey interactions, competition, symbiosis, and successional changes. The overall goal is to benefit human and non-human communities in the ecological sphere, with fewer negative environmental or social impacts and fewer external inputs (Vandermeer et al. 1998; Altieri et al. 1998). From a food system focus, agroecology provides management options in terms of commercialisation and consumption through the promotion of short food chains and healthy diets (Pimbert and Lemke 2018; Loconto et al. 2018).

Agroecology has been proposed as a key set of practices in building climate resilience (FAO et al. 2018; Altieri et al. 2015). These can enhance on-farm diversity (of genes, species, and ecosystems) through a landscape approach (FAO 2018g). Outcomes include soil conservation and restoration and thus soil carbon sequestration, reduction of the use of mineral and chemical fertilisers, watershed protection, promotion of local food systems, waste reduction, and fair access to healthy food through nutritious and diversified diets (Pimbert and Lemke 2018; Kremen et al. 2012; Goh 2011; Gliessman and Engles 2014).

A principle in agroecology is to contribute to food production by smallholder farmers (Altieri 2002). Since climatic events can severely impact smallholder farmers, there is a need to better understand the heterogeneity of small-scale agriculture in order to consider the diversity of strategies that traditional farmers have used and still use to deal with climatic variability. In Africa, many smallholder farmers cope with and even prepare for climate extremes, minimising crop failure through a series of agroecological practices (e.g., biodiversification, soil management, and water harvesting) (Mbow et al. 2014a). Resilience to extreme climate events is also linked to on-farm biodiversity, a typical feature of traditional farming systems (Altieri and Nicholls 2017).

Critiques of agroecology refer to its explicit exclusion of modern biotechnology (Kershen 2013) and the assumption that smallholder farmers are a uniform unit with no heterogeneity in power (and thus gender) relationships (Neira and Montiel 2013; Siliprandi and Zuluaga Sánchez 2014).

5.6.4.2 Climate-smart agriculture

'Climate-smart agriculture' (CSA) is an approach developed to tackle current food security and climate change challenges in a joint and synergistic fashion (Lipper et al. 2014; Aggarwal et al. 2018; FAO 2013c). CSA is designed to be a pathway towards development and food security built on three pillars: increasing productivity and incomes, enhancing resilience of livelihoods and ecosystems and reducing, and removing GHG emissions from the atmosphere (FAO 2013c). Climate-smart agricultural systems are integrated approaches to the closely linked challenges of food security, development, and climate change adaptation/mitigation to enable countries to identify options with maximum benefits and those where trade-offs need management.

Many agricultural practices and technologies already provide proven benefits to farmers' food security, resilience and productivity (Dhanush and Vermeulen 2016). In many cases, these can be implemented by changing the suites of management practices. For example, enhancing soil organic matter to improve the water-holding capacity of agricultural landscapes also sequesters carbon. In annual cropping systems, changes from conventional tillage practices to minimum tillage can convert the system from one that either provides adaptation or mitigation benefits or neither to one that provides both adaptation and mitigation benefits (Sapkota et al. 2017a; Harvey et al. 2014a).

Increasing food production by using more fertilisers in agricultural fields could maintain crop yield in the face of climate change, but may result in greater overall GHG emissions. But increasing or maintaining the same level of yield by increasing nutrient-use-efficiency through adoption of better fertiliser management practices could contribute to both food security and climate change mitigation (Sapkota et al. 2017a).

Mixed farming systems integrating crops, livestock, fisheries and agroforestry could maintain crop yield in the face of climate change, help the system to adapt to climatic risk, and minimise GHG emissions by increasingly improving the nutrient flow in the system (Mbow et al. 2014a; Newaj et al. 2016; Bioversity International 2016). Such systems can help diversify production and/or incomes and support efficient and timely use of inputs, thus contributing to increased resilience, but they require local seed and input systems and extension services. Recent whole farm modelling exercises have shown the economic and environmental (reduced GH emissions, reduced land use) benefits of integrated crop-livestock systems (Gil et al. 2018) compared different soy-livestock systems across multiple economic and environmental indicators, including climate resilience. However, it is important to note that potential benefits are very context specific.

Although climate-smart agriculture involves a holistic approach, some argue that it narrowly focuses on technical aspects at the production level (Taylor 2018; Newell and Taylor 2018). Studying barriers to the adoption and diffusion of technological innovations for climate-smart agriculture in Europe, Long et al. (2016) found that there was incompatibility between existing policies and climate-smart agriculture objectives, including barriers to the adoption of technological innovations.

Climate-smart agricultural systems recognise that the implementation of the potential options will be shaped by specific country contexts and capacities, as well as enabled by access to better information, aligned policies, coordinated institutional arrangements and flexible incentives and financing mechanisms (Aggarwal et al. 2018). Attention to underlying socio-economic factors that affect adoption of practices and access to technologies is crucial for enhancing biophysical processes, increasing productivity, and reducing GHG emissions at scale. The Government of India, for example, has started a programme of climate resilient villages (CRV) as a learning platform to design, implement, evaluate and promote various climate-smart agricultural interventions, with the goal of ensuring enabling mechanisms at the community level (Srinivasa Rao et al. 2016).

5.6.4.3 Conservation agriculture

Conservation agriculture (CA) is based on the principles of minimum soil disturbance and permanent soil cover, combined with appropriate crop rotation (Jat et al. 2014; FAO 2011e). CA has been shown to respond with positive benefits to smallholder farmers under both economic and environmental pressures (Sapkota et al. 2017a, 2015). This agricultural production system uses a body of soil and residues management practices that control erosion (Blanco Sepúlveda and Aguilar Carrillo 2016) and at the same time improve soil quality, by increasing organic matter content and improving porosity, structural stability, infiltration and water retention (Sapkota et al. 2017a, 2015 and Govaerts et al. 2009).

Intensive agriculture during the second half of the 20th century led to soil degradation and loss of natural resources and contributed to climate change. Sustainable soil management practices can address both food security and climate change challenges faced by these agricultural systems. For example, sequestration of soil organic carbon (SOC) is an important strategy to improve soil quality and to mitigation of climate change (Lal 2004). CA has been reported to increase farm productivity by reducing costs of production (Aryal et al. 2015; Sapkota et al. 2015; Indoria et al. 2017) as well as to reduce GHG emission (Pratibha et al. 2016).

Conservation agriculture brings favourable changes in soil properties that affect the delivery of nature's contribution to people (NCPs) or ecosystem services, including climate regulation through carbon sequestration and GHG emissions (Palm et al. 2013; Sapkota et al. 2017a). However, by analysing datasets for soil carbon in the tropics, Powlson et al. (2014, 2016) argued that the rate of SOC increase and resulting GHG mitigation in CA systems, from zero-tillage in particular, has been overstated (Chapter 2).

However, there is unanimous agreement that the gain in SOC and its contribution to GHG mitigation by CA in any given soil is largely determined by the quantity of organic matter returned to the soil (Giller et al. 2009; Virto et al. 2011; Sapkota et al. 2017b). Thus, a careful analysis of the production system is necessary to minimise the trade-offs among the multiple use of residues, especially where residues remain an integral part of livestock feeding (Sapkota et al. 2017b). Similarly, replacing mono-cropping systems with more diversified cropping systems and agroforestry, as well as afforestation and deforestation, can buffer temperatures as well as increase carbon storage (Mbow et al. 2014a; Bioversity International 2016), and provide diversified and healthy diets in the face of climate change.

Adoption of conservation agriculture in Africa has been low despite more than three decades of implementation (Giller et al. 2009), although there is promising uptake recently in east and southern Africa. This calls for a better understanding of the social and institutional aspects around CA adoption. Brown et al. (2017a) found that institutional and community constraints hampered the use of financial, physical, human and informational resources to implement CA programmes.

Gender plays an important role at the intra-household level in regard to decision-making and distributing benefits. Conservation agriculture interventions have implications for labour requirements, labour allocation, and investment decisions, all of which impact the roles of men and women (Farnworth et al. 2016) (Section 5.1.3). For example, in the Global South, CA generally reduces labour and production costs and generally leads to increased returns to family labour (Aryal et al. 2015) although a gender shift of the labour burden to women have also been described (Giller et al. 2009).

5.6.4.4 Sustainable intensification

The need to produce about 50% more food by 2050, required to feed the increasing world population (FAO 2018a), may come at the price of significant increases in GHG emissions and environmental impacts, including loss of biodiversity. For instance, land conversion for agriculture is responsible for an estimated 8–10% of all anthropogenic GHG emissions currently (Section 5.4). Recent calls for sustainable intensification (SI) are based on the premise that damage to the environment through extensification outweighs benefits of extra food produced on new lands (Godfray 2015). However, increasing the net production area by restoring already degraded land may contribute to increased production on the one hand and increased carbon sequestration on the other (Jat et al. 2016), thereby contributing to both increased agricultural production and improved natural capital outcomes (Pretty et al. 2018).

Sustainable intensification is a goal but does not specify *a priori* how it could be attained, for example, which agricultural techniques to deploy (Garnett et al. 2013). It can be combined with selected other improved management practices, for example, conservation agriculture (see above), or agroforestry, with additional economic, ecosystem services, and carbon benefits. Sustainable intensification, by improving nutrient, water, and other input-use efficiency, not only helps to close yield gaps and contribute to food security (Garnett et al. 2013), but also reduces the loss of such production inputs and associated emissions (Sapkota et al. 2017c; Wollenberg et al. 2016). Closing yield gaps is a way to become more efficient in use of land per unit production. Currently, most regions in Africa and South Asia have attained less than 40% of their potential crop production (Pradhan et al. 2015). Integrated farming systems (e.g., mixed crop/livestock, crop/aquaculture) are strategies to produce more products per unit land, which in regard to food security, becomes highly relevant.

Sustainable intensification acknowledges that enhanced productivity needs to be accompanied by maintenance of other ecosystem services and enhanced resilience to shocks (Vanlauwe et al. 2014). SI in intensively farmed areas may require a reduction in production in favour of increasing sustainability in the broad sense (Buckwell et al. 2014) (Cross-Chapter Box 6 in Chapter 5). Hence, moving towards sustainability may imply lower yield growth rates than those maximally attainable in such situations. For areas that contain valuable natural ecosystems, such as the primary forest in the Congo basin, intensification of agriculture is one of the pillars of the strategy to conserve forest (Vanlauwe et al. 2014). Intensification in agriculture is recognised as one of the pathways to meet food security and climate change adaptation and mitigation goals (Sapkota et al. 2017c).

However, SI does not always confer co-benefits in terms of food security and climate change adaption/mitigation. For example, in the case of Vietnam, intensified production of rice and pigs reduced GHG emissions in the short term through land sparing, but after two decades, the emissions associated with higher inputs were likely to outweigh the savings from land sparing (Thu Thuy et al. 2009). Intensification needs to be sustainable in all components of food system by curbing agricultural sprawl, rebuilding soils, restoring degraded lands, reducing agricultural pollution, increasing water use efficiency, and decreasing the use of external inputs (Cook et al. 2015).

A study conducted by Palm et al. (2010) in Sub-Saharan Africa, reported that, at low population densities and high land availability, food security and climate mitigation goals can be met with intensification scenarios, resulting in surplus crop area for reforestation. In contrast, for high population density and small farm sizes, attaining food security and reducing GHG emissions require the use of more mineral fertilisers to make land available for reforestation. However, some forms of intensification in drylands can increase rather than reduce vulnerability due to adverse effects such as environmental degradation and increased social inequity (Robinson et al. 2015).

Sustainable intensification has been critiqued for considering food security only from the supply side, whereas global food security requires attention to all aspects of food system, including access, utilisation, and stability (Godfray 2015). Further, adoption of high-input forms of agriculture under the guise of simultaneously improving yields and environmental performance will attract more investment leading to higher rate of adoption but with the environmental component of SI quickly abandoned (Godfray 2015). Where adopted, SI needs to engage with the sustainable development agenda to (i) identify SI agricultural practices that strengthen rural communities, improve smallholder livelihoods and employment, and avoid negative social and cultural impacts, including loss of land tenure and forced migration; (ii) invest in the social, financial, natural, and physical capital needed to facilitate SI implementation; and (iii) develop mechanisms to pay poor farmers for undertaking sustainability measures (e.g., GHG emissions mitigation or biodiversity protection) that may carry economic costs (Garnett et al. 2013).

In summary, integrated agricultural systems and practices can enhance food system resilience to climate change and reduce GHG emissions, while helping to achieve sustainability (*high confidence*).

Cross-Chapter Box 6 | Agricultural intensification: Land sparing, land sharing and sustainability

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Introduction

The projected demand for more food, fuel and fibre for a growing human population necessitates intensification of current land use to avoid conversion of additional land to agriculture and potentially allow the sparing of land to provide other ecosystem services, including carbon sequestration, production of biomass for energy, and the protection of biodiversity (Benton et al. 2018; Garnett et al. 2013). Land-use intensity may be defined in terms of three components; (i) intensity of system inputs (land/soil, capital, labour, knowledge, nutrients and other chemicals), (ii) intensity of system outputs (yield per unit land area or per specific input) and (iii) the impacts of land use on ecosystem services such as changes in soil carbon or biodiversity (Erb et al. 2013). Intensified land use can lead to ecological damage as well as degradation of soil, resulting in a loss of function which underpins many ecosystem services (Wilhelm and Smith 2018; Smith et al. 2016). Therefore, there is a risk that increased agricultural intensification could deliver short-term production goals at the expense of future productive potential, jeopardising long term food security (Tilman et al. 2011).

Agroecosystems which maintain or improve the natural and human capital and services they provide may be defined as sustainable systems, while those which deplete these assets as unsustainable (Pretty and Bharucha 2014). Producing more food, fuel and fibre without the conversion of additional non-agricultural land while simultaneously reducing environmental impacts requires what has been termed sustainable intensification (Godfray et al. 2010; FAO 2011e) (Glossary and Figure 1 in this Cross-Chapter Box). Sustainable intensification (SI) may be achieved through a wide variety of means; from improved nutrient and water use efficiency via plant and animal breeding programmes, to the implementation of integrated soil fertility and pest management practices, as well as by smarter land-use allocation at a larger spatial scale: for example, matching land use to the context and specific capabilities of the land (Benton et al. 2018). However, implementation of SI is broader than simply increasing the technical efficiency of agriculture ('doing more with less'). It sometimes may require a reduction of yields to raise sustainability, and successful implementation can be dependent on place and scale. Pretty et al. (2018), following Hill (1985), highlights three elements to SI: (i) increasing efficiency, (ii) substitution of less beneficial or efficient practices for better ones, and (iii) system redesign to adopt new practices and farming systems (Table 1 in this Cross-Chapter Box).

Under a land sparing strategy, intensification of land use in some areas, generating higher productivity per unit area of land, can allow other land to provide other ecosystem services, such as increased carbon sequestration and the conservation of natural ecosystems and biodiversity (Balmford et al. 2018 and Strassburg et al. 2014). Conversely under a land sharing strategy, less, or no, land is set aside, but lower levels of intensification are applied to agricultural land, providing a combination of provisioning and other functions such as biodiversity conservation from the same land (Green et al. 2005). The two approaches are not mutually exclusive and the suitability of their application is generally system-, scale- and/or location-specific (Fischer et al. 2014). One crucial issue for the success of a land sparing strategy is that spared land is protected from further conversion. As the profits from the intensively managed land increase, there is an incentive for conversion of additional land for production (Byerlee et al. 2014). Furthermore, it is implicit that there are limits to the SI of land at a local and also planetary boundary level (Rockström et al. 2009). These may relate to the 'health' of soil, the presence of supporting services, such as pollination, local limits to water availability, or limits on air quality. This implies that it may not be possible to meet demand 'sustainably' if demand exceeds local and global limits. There are no single global solutions to these challenges and specific in situ responses for different farming systems and locations are required. Bajželj et al. (2014) showed that implementation of SI, primarily through yield gap closure, had better environmental outcomes compared with 'business as usual' trajectories. However, SI alone will not be able to deliver the necessary environmental outcomes from the food system – dietary change and reduced food waste are also required (Springmann et al. 2018a; Bajželj et al. 2014).

Cross-Chapter Box 6 (continued)

Cross-Chapter Box 6, Table 1 | Approaches to sustainable intensification of agriculture (Pretty et al. 2018; Hill 1985).

Approach	Sub-category	Examples/notes
Improving efficiency	Precision agriculture	High- and low-technology options to optimise resource use.
	Genetic improvements	Improved resource use efficiency through crop or livestock breeding.
	Irrigation technology	Increased production in areas currently limited by precipitation (sustainable water supply required).
	Organisational scale-up	Increasing farm organisational scale (e.g., cooperative schemes) can increase efficiency via facilitation of mechanisation and precision techniques.
Substitution	Green fertiliser	Replacing chemical fertiliser with green manures, compost (including vermicompost), biosolids and digestate (by-product of anaerobic digestion) to maintain and improve soil fertility.
	Biological control	Pest control through encouraging natural predators.
	Alternative crops	Replacment of annual with perennial crops reducing the need for soil disturbance and reducing erosion.
	Premium products	Increase farm-level income for less output by producing a premium product.
System redesign	System diversification	Implementation of alternative farming systems: organic, agroforestry and intercropping (including the use of legumes).
	Pest management	Implementing integrated pest and weed management to reduce the quantities of inputs required.
	Nutrient management	Implementing integrated nutrient management by using crop and soil specific nutrient management – guided by soil testing.
	Knowledge transfer	Using knowledge sharing and technology platforms to accelerate the uptake of good agricultural practices.

Improved efficiency – example of precision agriculture

Precision farming usually refers to optimising production in fields through site-specific choices of crop varieties, agrochemical application, precise water management (e.g., in given areas or threshold moistures) and management of crops at a small scale (or livestock as individuals) (Hedley 2015). Precision agriculture has the potential to achieve higher yields in a more efficient and sustainable manner compared with traditional low-precision methods.

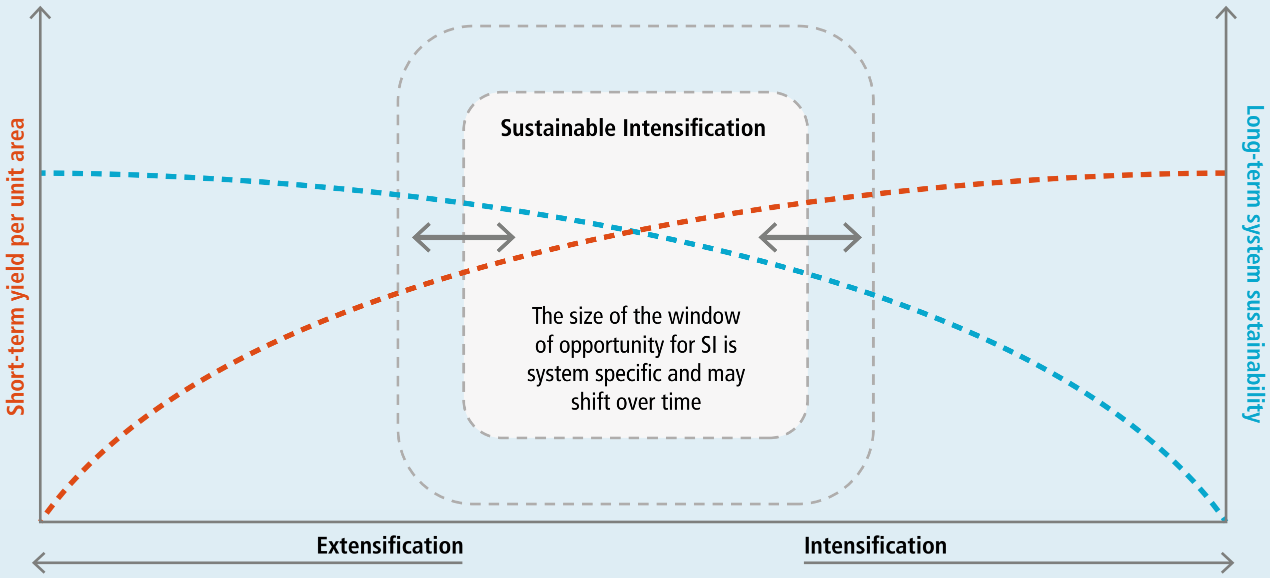
Precision agriculture

Precision agriculture is a technologically advanced approach that uses continual monitoring of crop and livestock performance to actively inform management practices. Precise monitoring of crop performance over the course of the growing season will enable farmers to economise on their inputs in terms of water, nutrients and pest management. Therefore, it can contribute to both the food security (by maintaining yields), sustainability (by reducing unnecessary inputs) and land sparing goals associated with SI. The site-specific management of weeds allows a more efficient application of herbicide to specific weed patches within crops (Jensen et al. 2012). Such precision weed control has resulted in herbicide savings of 19–22% for winter oilseed rape, 46–57% for sugar beet and 60–77% for winter wheat production (Gutjahr and Gerhards 2010). The use of on-farm sensors for real time management of crop and livestock performance can enhance farm efficiency (Aqeel-Ur-Rehman et al. 2014). Mapping soil nutrition status can allow for more targeted, and therefore more effective, nutrient management practices (Hedley 2015). Using wireless sensors to monitor environmental conditions, such as soil moisture, has the potential to allow more efficient crop irrigation (Srbinovska et al. 2015). Controlled traffic farming, where farm machinery is confined to permanent tracks, using automatic steering and satellite guidance, increases yields by minimising soil compaction. However, barriers to the uptake of many of these high-tech precision agriculture technologies remain. In what is described as the 'implementation problem', despite the potential to collect vast quantities of data on crop or livestock performance, applying these data to inform management decisions remains a challenge (Lindblom et al. 2017).

Low-tech precision agriculture

The principle of precision agriculture can be applied equally to low capital-input farming, in the form of low-tech precision agriculture (Conway 2013). The principle is the same, but instead of adopting capital-heavy equipment (such as sensor technology connected to the 'internet of things', or large machinery and expensive inputs), farmers use knowledge and experience and re-purposed innovative approaches, such as a bottle cap as a fertiliser measure for each plant, applied by hand (Mondal and Basu 2009). This type of precision agriculture is particularly relevant to small-scale farming in the Global South, where capital investment is major limiting factor. For example, the application of a simple seed priming technique resulted in a 20 to 30% increase in yields of pearl millet and sorghum in semi-arid West Africa (Aune et al. 2017). Low-tech precision agriculture has the potential to increase the economic return per unit land area while also creating new employment opportunities.

Cross-Chapter Box 6 (continued)



Cross-Chapter Box 6, Figure 1 | There is a need to balance increasing demands for food, fuel and fibre with long-term sustainability of land use. Sustainable intensification can, in theory, offer a window of opportunity for the intensification of land use without causing degradation. This potentially allows the sparing of land to provide other ecosystem services, including carbon sequestration and the protection of biodiversity. However, the potential for SI is system specific and may change through time (indicated by grey arrows). Current practice may already be outside of this window and be unsustainable in terms of negative impacts on the long-term sustainability of the system.

Sustainable intensification through farming system redesign

Sustainable intensification requires equal weight to be placed on the sustainability and intensification components (Benton 2016; Garnett et al. 2013). Figure 1 in this Cross-Chapter Box outlines the trade-offs which SI necessitates between the intensity of land use against long-term sustainability. One approach to this challenge is through farming system redesign, including increased diversification.

Diversification of intensively managed systems

Incorporating higher levels of plant diversity in agroecosystems can improve the sustainability of farming systems (Isbell et al. 2017). Where intensive land use has led to land degradation, more diverse land-use systems, such as intercropping, can provide a more sustainable land-use option with co-benefits for food security, adaptation and mitigation objectives. For example, in temperate regions, highly productive agricultural grasslands used to produce meat and dairy products are characterised by monoculture pastures with high agrochemical inputs. Multi-species grasslands may provide a route to SI, as even a modest increase in species richness in intensively managed grasslands can result in higher forage yields without increased inputs, such as chemical fertiliser (Finn et al. 2013; Sanderson et al. 2013; Tilman et al. 2011). Recent evidence also indicates multispecies grasslands have greater resilience to drought, indicating co-benefits for adaptation (Hofer et al. 2016; Haughey et al. 2018).

Diversification of production systems

Agroforestry systems (see Glossary) can promote regional food security and provide many additional ecosystem services when compared with monoculture crop systems. Co-benefits for mitigation and adaptation include increased carbon sequestration in soils and biomass, improved water and nutrient use efficiency and the creation of favourable micro-climates (Waldron et al. 2017). Silvopasture systems, which combine grazing of livestock and forestry, are particularly useful in reducing land degradation where the risk of soil erosion is high (Murgueitio et al. 2011). Crop and livestock systems can also be combined to provide multiple services. Perennial wheat derivatives produced both high quality forage and substantial volumes of cereal grains (Newell and Hayes 2017), and show promise for integrating cereal and livestock production while sequestering soil carbon (Ryan et al. 2018). A key feature of diverse production systems is the provision of multiple income streams for farming households, providing much needed economic resilience in the face of fluctuation of crop yields and prices.

Cross-Chapter Box 6 (continued)

Landscape approaches

The land sparing and land sharing approaches which may be used to implement SI are inherently 'landscape approaches' (e.g., Hodgson et al. 2010). While the term landscape is by no means precise (Englund et al. 2017), landscape approaches, focused, for example, at catchment scale, are generally agreed to be the best way to tackle competing demands for land (e.g., Sayer et al. 2013), and are the appropriate scale at which to focus the implementation of sustainable intensification. The landscape approach allots land to various uses – cropping, intensive and extensive grazing, forestry, mining, conservation, recreation, urban, industry, infrastructure – through a planning process that seeks to balance conservation and production objectives. With respect to SI, a landscape approach is pertinent to achieving potential benefits for biodiversity conservation, ensuring that land 'spared' through SI remains protected, and that adverse impacts of agriculture on conservation land are minimised. Depending on the land governance mechanisms applied in the jurisdiction, different approaches will be appropriate/required. However, benefits are only assured if land-use restrictions are devised and enforced.

Summary

Intensification needs to be achieved sustainably, necessitating a balance between productivity today and future potential (*high agreement, medium evidence*). Improving the efficiency of agriculture systems can increase production per unit of land through more effective resource use. To achieve SI, some intensively managed agricultural systems may have to be diversified as they cannot be further intensified without land degradation. A combination of land sparing and sharing options can be utilised to achieve SI – their application is most likely to succeed if applied using a landscape approach.

5.6.5 Role of urban agriculture

Cities are an important actor in the food system through demand for food by urban dwellers and production of food in urban and peri-urban areas (Cross-Chapter Box 4 in Chapter 2). Both the demand side and supply side roles are important relative to climate change mitigation and adaptation strategies. Urban areas are home to more than half of the world's population, and a minimal proportion of the production. Thus, they are important drivers for the development of the complex food systems in place today, especially with regard to supply chains and dietary preferences.

The increasing separation of urban and rural populations with regard to territory and culture is one of the factors favouring the nutrition transition towards urban diets (Weber and Matthews 2008; Neira et al. 2016). These are primarily based on a high diversity of food products, independent of season and local production, and on the extension of the distances that food travels between production and consumption. The transition of traditional diets to more homogeneous diets has also become tied to consumption of animal protein, which has increased GHG emissions globally (Section 5.4.6).

Cities are becoming key actors in developing strategies of mitigation to climate change, in their food procurement and in sustainable urban food policies alike (McPhearson et al. 2018). These are being developed by big and medium-sized cities in the world, often integrated within climate change policies (Moragues et al. 2013 and Calori and Magarini 2015). A review of 100 cities shows that urban food consumption is one of the largest sources of urban material flows, urban carbon footprint, and land footprint (Goldstein et al. 2017). Additionally, the urban poor have limited capacity to adapt to climate-related impacts, which place their food security at risk under climate change (Dubbeling and de Zeeuw 2011).

Urban and peri-urban areas. In 2010, around 14% of the global population was nourished by food grown in urban and peri-urban areas (Kriewald et al. 2019). A review study on Sub-Saharan Africa shows that urban and peri-urban agriculture contributes to climate change adaptation and mitigation (Lwasa et al. 2014, 2015). Urban and peri-urban agriculture reduces the food carbon footprint by avoiding long distance food transport. These types of agriculture also limit GHG emissions by recycling organic waste and wastewater that would otherwise release methane from landfills and dumping sites (Lwasa et al. 2014). Urban and peri-urban agriculture also contribute in adapting to climate change, including extreme events, by reducing the urban heat island effect, increasing water infiltration and slowing down run-offs to prevent flooding, etc. (Lwasa et al. 2014, 2015; Kumar et al. 2017a). For example, a scenario analysis shows that urban gardens reduce the surface temperature up to 10°C in comparison to the temperature without vegetation (Tsilini et al. 2015). Urban agriculture can also improve biodiversity and strengthen associated ecosystem services (Lin et al. 2015).

Urban and peri-urban agriculture is exposed to climate risks and urban growth that may undermine its long-term potential to address urban food security (Padgham et al. 2015). Therefore, there is a need to better understand the impact of urban sprawl on peri-urban agriculture; the contribution of urban and peri-urban agriculture to food self-sufficiency of cities; the risks posed by pollutants from urban areas to agriculture and vice-versa; the global and regional extent of urban agriculture; and the role that urban agriculture could play in climate resilience and abating malnutrition (Mok et al. 2014; Hamilton et al. 2014). Globally, urban sprawl is projected to consume 1.8–2.4% and 5% of the current cultivated land by 2030 and 2050 respectively, leading to crop calorie loss of 3–4% and 6–7%, respectively (Pradhan et al. 2014 and Bren d'Amour et al. 2017). Kriewald et al. 2019 shows that the urban growth has

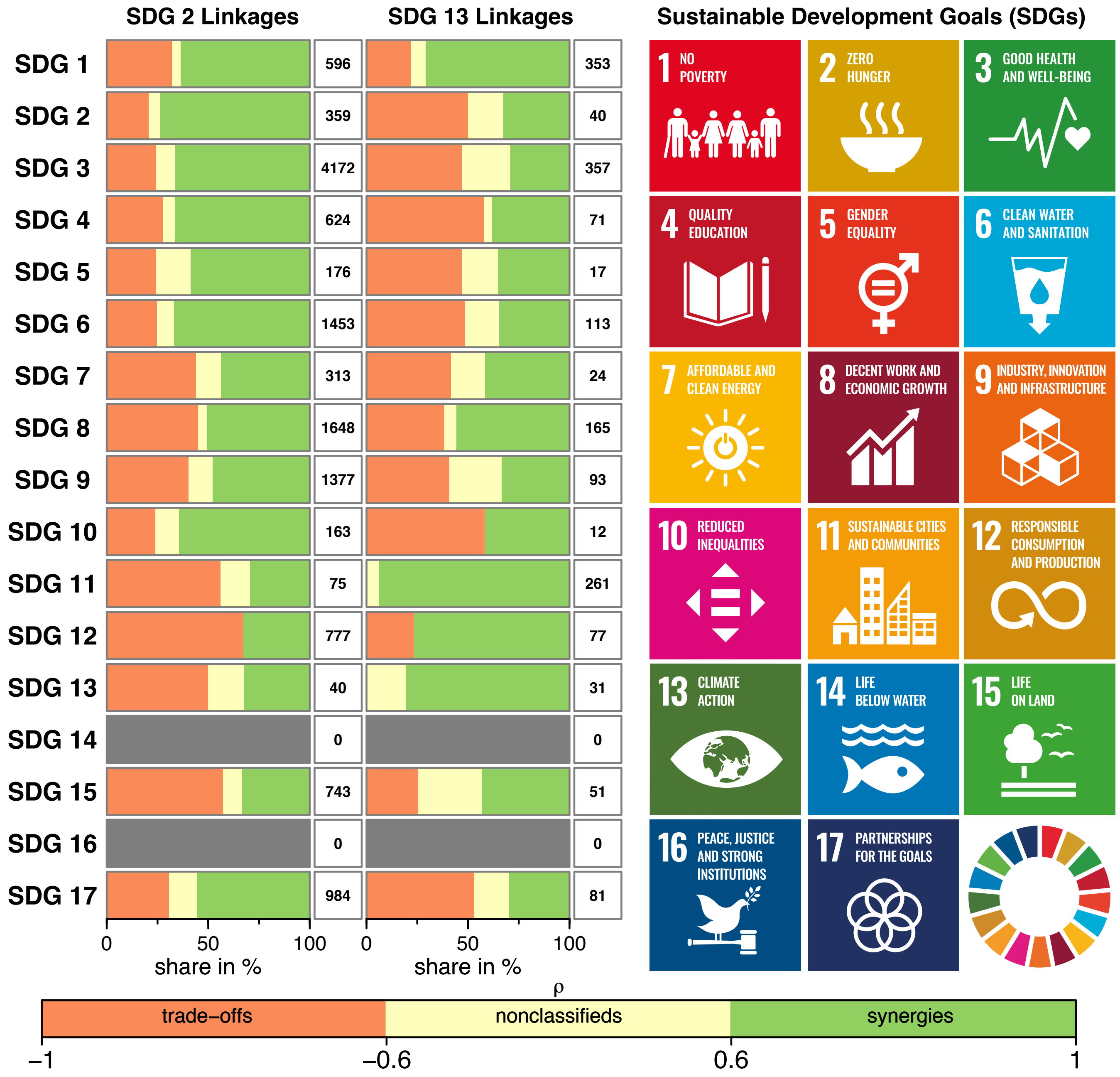


Figure 5.16.| Intra and inter-linkages for SDG 2 (Zero Hunger) and SDG 13 (Climate Action) at the global level using the official indicators of Sustainable Development Goals that consist of data for 122 indicators for a total of 227 countries between the years 1983 and 2016 (United Nations Statistics Division 2016). Synergies and trade-offs defined as significant positive ($\rho > 0.6$, red bar) and negative ($\rho < –0.6$, green bar) Spearman's correlation between SDG indicators, respectively; ρ between 0.6 and –0.6 is considered as nonclassifieds (yellow bar) (Pradhan et al. 2017). Grey bars show insufficient data for analysis; white box shows number of data pairs used in analysis. The correlation between unique pairs of indicator time-series is carried based on country data. For example, between 'prevalence of undernourishment' (an indicator for SDG 2.1) and 'maternal mortality ratio' (an indicator for SDG 3.1). The data pairs can belong to the same goal or to two distinct goals. At the global level, intra-linkages of SDGs are quantified by the percentage of synergies, trade-offs, and nonclassifieds of indicator pairs belonging to the same SDG for all the countries. Similarly, SDG interlinkages are estimated by the percentage of synergies, trade-offs, and nonclassifieds between indicator pairs that fall into two distinct goals for all the countries.

the largest impact in many sub-continental regions (e.g., Western, Central, and Eastern Africa), while climate change will mostly reduce potential of urban and peri-urban agriculture in Southern Europe and North Africa.

In summary, urban and peri-urban agriculture can contribute to improving urban food security, reducing GHG emissions, and adapting to climate change impacts *(robust evidence, medium agreement).*

5.6.6 Links to the Sustainable Development Goals

In 2015, the Sustainable Development Goals (SDGs) and the Paris Agreement were two global major international policies adopted by all countries to guide the world to overall sustainability, within the 2030 Sustainable Development Agenda and UNFCCC processes respectively. The 2030 Sustainable Development agenda includes 17 goals and 169 targets, including zero hunger, sustainable agriculture and climate action (United Nations 2015).

This section focuses on intra – and inter-linkages of SDG 2 and SDG 13 based on the official SDG indicators (Figure 5.16), showing the current conditions (Roy et al. (2018) and Chapter 7 for further discussion). The second goal (Zero Hunger – SDG 2) aims to end hunger and all forms of malnutrition by 2030 and commits to universal access to safe, nutritious and sufficient food at all times of the year. SDG 13 (Climate Action) calls for urgent action to combat climate change and its impacts. Integrating the SDGs into the global food system can provide opportunities for mitigation and adaptation and enhancement of food security.

Ensuring food security (SDG 2) shows positive relations (synergies) with most goals, according to Pradhan et al. (2017) and the International Council for Science (ICSU) (2017), but has trade-offs with SDG 12 (Responsible Consumption and Production) and SDG 15 (Life on Land) under current development paradigms (Pradhan et al. 2017). Sustainable transformation of traditional consumption and production approaches can overcome these trade-offs based on several innovative methods (Shove et al. 2012). For example, sustainable intensification and reduction of food waste can minimise the observed negative relations between SDG 2 and other goals (Obersteiner et al. 2016) (Cross-Chapter Box 6 in Chapter 5 and Section 5.5.2). Achieving target 12.3 of SDG 12 'by 2030, to halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses' will contribute to climate change mitigation.

Doubling productivity of smallholder farmers and halving food loss and waste by 2030 are targets of SDG 2 and SDG 12, respectively (United Nations Statistics Division 2016). Agroforestry that promotes biodiversity and sustainable land management also contributes to food security (Montagnini and Metzel 2017). Land restoration and protection (SDG 15) can increase crop productivity (SDG 2) (Wolff et al. 2018). Similarly, efficient irrigation practices can reduce water demand for agriculture that could improve the health of the freshwater ecosystem (SDG 6 and SDG 15) without reducing food production (Jägermeyr et al. 2017).

Climate action (SDG 13) shows negative relations (trade-offs) with most goals and is antagonistic to the 2030 development agenda under the current development paradigm (Figure 5.16) (Lusseau and Mancini 2019 and Pradhan 2019). The targets for SDG 13 have a strong focus on climate change adaptation, and the data for the SDG 13 indicators are limited. SDG 13 shares two indicators with SDG 1 and SDG 11 (United Nations 2017) and therefore, has mainly positive linkages with these two goals. Trade-offs were observed between SDG 2 and SDG 13 for around 50% of the linkages analysed (Pradhan et al. 2017).

Transformation from current development paradigms and the breaking of these lock-in effects can protect climate and achieve food security in future. Sustainable agriculture practices can provide climate change adaptation and mitigation synergies, linking SDG 2 and SDG 13 more positively, according to the International Council for Science (ICSU) (2017). IPCC found that most of the current observed trade-offs between SDG 13 and other SDGs can be converted into synergies based on various mitigation options that can be deployed to limit the global warming well below 1.5°C (IPCC 2018b).

In summary, there are fundamental synergies that can facilitate the joint implementation of strategies to achieve SDGs and climate action, with particular reference to those climate response strategies related to both supply side (production and supply chains) and demand side (consumption and dietary choices) described in this chapter (*high agreement and medium evidence*).

5.7 Enabling conditions and knowledge gaps

To achieve mitigation and adaptation to climate change in food systems, enabling conditions are needed to scale up the adoption of effective strategies (such as those described in Sections 5.3 to 5.6 and Chapter 6). These enabling conditions include multi-level governance and multi-sector institutions (Supplementary Material Section SM5.7) and multiple policy pathways (Sections 5.7.1 and 5.7.2). In this regard, the subnational level is gaining relevance both in food systems and climate change. Just Transitions are needed to address both climate change and food security (Section 5.7.3). Mobilisation of knowledge, education, and capacity will be required (Section 5.7.4) to fill knowledge gaps (Section 5.7.5).

Effective governance of food systems and climate change requires the establishment of institutions responsible for coordinating among multiple sectors (education, agriculture, environment, welfare, consumption, economic, health), levels (local, regional, national, global) and actors (governments, CSO, public sector, private sector, international bodies). Positive outcomes will be engendered by participation, learning, flexibility, and cooperation. See Supplementary Material SM5.7 for further discussion.

5.7.1 Enabling policy environments

The scope for responses to make sustainable land use inclusive of climate change mitigation and adaptation, and the policies to implement them, are covered in detail in Chapters 6 and 7. Here we highlight some of the major policy areas that have shaped the food system, and might be able to shape responses in future. Although two families of policy – agriculture and trade – have been instrumental in shaping the food system in the past (and potentially have led to conditions that increase climate vulnerability) (Benton and Bailey 2019), a much wider family of policy instruments can be deployed to reconfigure the food system to deliver healthy diets in a sustainable way.

5.7.1.1 Agriculture and trade policy

Agriculture. The thrust of agricultural policies over the last 50 years has been to increase productivity, even if at the expense of environmental sustainability (Benton and Bailey 2019). For example, in 2007–2009, 46% of OECD support for agriculture was based on measures of output (price support or payments based on yields), 37% of support was based on the current or historical area planted, herd size (or correlated measures of the notional costs of farming), and 13% was payments linked to input prices. In a similar vein, non-OECD countries have promoted productivity growth for their agricultural sectors.

Trade. Along with agricultural policy to grow productivity, the development of frameworks to liberalise trade (such as the General Agreement on Tariffs and Trade – GATT – Uruguay Round, now incorporated into the World Trade Organization) have been essential in stimulating the growth of a globalised food system. Almost every country has a reliance on trade to fulfil some or all of its local food needs, and trade networks have grown to be highly complex (Puma et al. 2015; MacDonald et al. 2015; Fader et al. 2013 and Ercsey-Ravasz et al. 2012). This is because many countries lack the capacity to produce sufficient food due to climatic conditions, soil quality, water constraints, and availability of farmland (FAO 2015b). In a world of liberalised trade, using comparative advantage to maximise production in high-yielding commodities, exporting excess production, and importing supplies of other goods supports economic growth.

City states as well as many small island states, do not have adequate farmland to feed their populations, while Sub-Saharan African countries are projected to experience high population growth as well as to be negatively impacted by climate change, and thus will likely find it difficult to produce all of their own food supplies (Agarwal et al. 2002). One study estimates that some 66 countries are currently incapable of being self-sufficient in food (Pradhan et al. 2014). Estimates of the proportion of people relying on trade for basic food security vary from about 16% to about 22% (Fader et al. 2013; Pradhan et al. 2014), with this figure rising to between 1.5 and 6 billion people by 2050, depending on dietary shifts, agricultural gains, and climate impacts (Pradhan et al. 2014).

Global trade is therefore essential for achieving food and nutrition security under climate change because it provides a mechanism for enhancing the efficiency of supply chains, reducing the vulnerability of food availability to changes in local weather, and moving production from areas of surplus to areas of deficit (FAO 2018d). However, the benefits of trade will only be realised if trade is managed in ways that maximise broadened access to new markets while minimising the risks of increased exposure to international competition and market volatility (Challinor et al. 2018; Brown et al. 2017b).

As described in Section 5.8.1, trade acts to buffer exposure to climate risks when the market works well. Under certain conditions – such as shocks, or the perception of a shock, coupled with a lack of food stocks or lack of transparency about stocks (Challinor et al. 2018; Marchand et al. 2016) – the market can fail and trade can expose countries to food price shocks.

Furthermore, Clapp (2016) showed that trade, often supported by high levels of subsidy support to agriculture in some countries, can depress world prices and reduce incomes for other agricultural exporters. Lower food prices that result from subsidy support may benefit urban consumers in importing countries, but at the same time they may hurt farmers' incomes in those same countries. The outmigration of smallholder farmers from the agriculture sector across the Global South is significantly attributed to these trade patterns of cheap food imports (Wittman 2011; McMichael 2014; Akram-Lodhi et al. 2013). Food production and trade cartels, as well as financial speculation on food futures markets, affect low-income market-dependent populations.

Food sovereignty is a framing developed to conceptualise these issues (Reuter 2015). They directly relate to the ability of local communities and nations to build their food systems, based, among other aspects, on diversified crops and ILK. If a country enters international markets by growing more commodity crops and reducing local crop varieties, it may get economic benefits, but may also expose itself to climate risks and food insecurity by increasing reliance on trade, which may be increasingly disrupted by climate risks. These include a local lack of resilience from reduced diversity of products, but also exposure to food price spikes, which can become amplified by market mechanisms such as speculation.

In summary, countries must determine the balance between locally produced versus imported food (and feed) such that it both minimises climate risks and ensures sustainable food security. There is *medium evidence* that trade has positive benefits but also creates exposure to risks (Section 5.3).

5.7.1.2 Scope for expanded policies

There are a range of ways that policy can intervene to stimulate change in the food system – through agriculture, research and development, food standards, manufacture and storage, changing the food environment and access to food, changing practices to encourage or discourage trade (Table 5.6). Novel incentives can stimulate the market, for example, through reduction in waste or changes in diets to gain benefits from a health or sustainability direction. Different contexts with different needs will require different set of policies at local, regional and national levels. See Supplementary Material Section SM5.7 for further discussion on expanded policies.

Table 5.6 | Potential policy 'families' for food-related adaptation and mitigation of climate change. The column 'scale' refers to scale of implementation: International (I), national (N), sub-national-regional (R), and local (L).

Family	Sub-family	Scale	Interventions	Examples
Supply-side efficiency	Increasing agricultural efficiency and yields	I, N	Agricultural R&D	Investment in research, innovation, knowledge exchange, e.g., on genetics, yield gaps, resilience
		I, N	Supporting precision agriculture	Agricultural engineering, robotics, big data, remote sensing, inputs
		I, N	Sustainable intensification projects	Soils, nutrients, capital, labour (Cross-Chapter Box 6)
		N, R	Improving farmer training and knowledge sharing	Extension services, online access, farmer field schools, farmer-to-farmer networks (CABI 2019)
	Land-use planning	N, R, L	Land-use planning for ecosystem services (remote sensing, ILK)	Zoning, protected area networks, multifunctional landscapes, 'land sparing' (Cross-Chapter Box 6; Benton et al. 2018; Jones et al. 2013)
		N, R, L	Conservation agriculture programmes	Soil and water erosion control, soil quality improvement (Conservation Evidence 2019)
		N	Payment for ecosystem services	Incentives for farmers/landowners to choose lower-profit but environmentally benign resource use, e.g., Los Negros Valley in Bolivia (Ezzine-de-Blas et al. 2016)
	Market approaches	I, N	Mandated carbon cost reporting in supply chains; public/private incentivised insurance products	Carbon and natural capital accounts (CDP 2019), crop insurance (Müller et al. 2017a)
	Trade	I	Liberalising trade flows; green trade	Reduction in GHG emissions from supply chains (Neumayer 2001)
Raising profitability and quality	Stimulating markets for premium goods	N, R	Sustainable farming standards, agroecology projects, local food movements	Regional policy development, public procurement of sustainable food (Mairie de Paris 2015)
Modifying demand	Reducing food waste	I, N, L	Regulations, taxes	'Pay-As-You-Throw (PAYT)' schemes; EU Landfill Directives; Japan Food Waste Recycling Law 2008; South Africa Draft Waste Classification and Management Regulations 2010 (Chalak et al. 2016)
		I, N, L	Awareness campaigns, education	FAO Global Initiative on Food Loss and Waste Reduction (FAO 2019b)
		I, N	Funding for reducing food waste	Research and investment for shelf life, processing, packaging, cold storage (MOFPI 2019)
		I, N, L	Circular economy using waste as inputs	Biofuels, distribution of excess food to charities (Baglioni et al. 2017)
	Reducing consumption of carbon-intensive food	I, N, L	Carbon pricing for selected food commodities	Food prices reflective of GHG gas emissions throughout production and supply chain (Springmann et al. 2017; Hasegawa et al. 2018)
		I, N, L	Changing food choice through education	Nutritional and portion-size labelling, 'nudge' strategies (positive reinforcement, indirect suggestion) (Arno and Thomas 2016)
		I, N, L	Changing food choices through money transfers	Unconditional cash transfers; e-vouchers exchanged for set quantity or value of specific, pre-selected goods (Fenn 2018)
		N, L	Changing food environments through planning	Farmers markets, community food production, addressing 'food deserts' (Ross et al. 2014)
	Combining carbon and health objectives	I, N, L	Changing subsidies, standards, regulations to healthier and more sustainably produced foods	USDA's 'Smart Snacks for School' regulation mandating nutritional guidelines (USDA 2016) Incentivising production via subsidies (direct to producer based on output or indirect via subsidising inputs)
		N	Preventative versus curative public healthcare incentives	Health insurance cost reductions for healthy and sustainable diets
		I, N, L	Food system labelling	Organic certification, nutrition labels, blockchain ledgers (Chadwick 2017)
		N, L	Education and awareness campaigns	School curricula; public awareness campaigns
		N, L	Investment in disruptive technologies (e.g., cultured meat)	Tax breaks for R&D, industrial strategies (European Union 2018)
		N, L	Public procurement	For health: Public Procurement of Food for Health (Caldeira et al. 2017) For environment: Paris Sustainable Food Plan 2015–2020 Public Procurement Code (Mairie de Paris 2015)

In summary, although agriculture is often thought to be shaped predominantly by agriculture and trade policies, there are over twenty families of policy areas that can shape agricultural production directly or indirectly (through environmental regulations or through markets, including by shaping consumer behaviour). Thus, delivering outcomes promoting climate change adaptation and mitigation can arise from policies across many departments, if suitably designed and aligned.

5.7.1.3 Health-related policies and cost savings

The co-benefits arising from mitigating climate change through changing dietary patterns, and thus demand, have potentially important economic impacts (*high confidence*). The gross value added from agriculture to the global economy (GVA) was 1.9 trillion USD2013 (FAO 2015c), from a global agriculture economy (GDP) of 2.7 trillion USD2016. In 2013, the FAO estimated an annual cost of 3.5 trillion USD for malnutrition (FAO 2013a).

However, this is likely to be an underestimate of the economic health costs of current food systems for several reasons: (i) lack of data – for example there is little robust data in the UK on the prevalence of malnutrition in the general population (beyond estimates of obesity and surveys of malnourishment of patients in hospital and care homes, from which estimates over 3 million people in the UK are undernourished (BAPEN 2012); (ii) lack of robust methodology to determine, for example, the exact relationship between over-consumption of poor diets, obesity and non-communicable diseases like diabetes, cardiovascular disease, a range of cancers or Alzheimer's disease (Pedditizi et al. 2016), and (iii) unequal healthcare spending around the world.

In the USA, the economic cost of diabetes, a disease strongly associated with obesity and affecting about 23 million Americans, is estimated at 327 billion USD2017 (American Diabetes Association 2018), with direct healthcare costs of 9600 USD per person. By 2025, it is estimated that, globally, there will be over 700 million people with diabetes (NCD-RisC 2016b), over 30 times the number in the USA. Even if a global average cost of diabetes per capita were a quarter of that in the USA, the total economic cost of diabetes would be approximately the same as global agricultural GDP. Finally, (iv) the role of agriculture in causing ill-health beyond dietary health, such as through degrading air quality (e.g., Paulot and Jacob 2014).

Whilst data of the healthcare costs associated with the food system and diets are scattered and the proportion of costs directly attributable to diets and food consumption is uncertain, there is potential for more preventative healthcare systems to save significant costs that could incentivise agricultural business models to change what is grown, and how. The potential of moving towards more preventative healthcare is widely discussed in health economics literature, particularly in order to reduce the life-style-related (including dietary-related) disease component in aging populations (e.g., Bloom et al. 2015).

5.7.1.4 Multiple policy pathways

As discussed in more detail in Chapters 6 and 7, there is a wide potential suite of interventions and policies that can potentially enhance the adaptation of food systems to climate change, as well as enhance the mitigation potential of food systems on climate change. There is an increasing number of studies that argue that the key to sustainable land management is not in land management practices but in the factors that determine the demand for products from land (such as food). Public health policy, therefore, has the potential to affect dietary choice and thus the demand for different amounts of, and types of, food.

Obersteiner et al. (2016) show that increasing the average price of food is an important policy lever that, by reducing demand, reduces food waste, pressure on land and water, impacts on biodiversity and through reducing emissions, mitigates climate change and potentially helps to achieve multiple SDGs. Whilst such policy responses – such as a carbon tax applied to goods including food – has the potential to be regressive, affecting the poor differentially (Frank et al. 2017; Hasegawa et al. 2018 and Kehlbacher et al. 2016), and increasing food insecurity – further development of social safety nets can help to avoid the regressive nature (Hasegawa et al. 2018). Hasegawa et al. (2018) point out that such safety nets for vulnerable populations could be funded from the revenues arising from a carbon tax.

The evidence suggests, as with SR15 (IPCC 2018a) and its multiple pathways to climate change solutions, that there is no single solution that will address the problems of food and climate change, but instead there is a need to deploy many solutions, simultaneously adapted to the needs and options available in a given context. For example, Springmann et al. (2018a) indicate that maintaining the food system within planetary boundaries at mid-century, including equitable climate, requires increasing the production (and resilience) of agricultural outputs (i.e., closing yield gaps), reducing waste, and changes in diets towards ones often described as flexitarian (low-meat dietary patterns that are in line with available evidence on healthy eating). Such changes can have significant co-benefits for public health, as well as facing significant challenges to ensure equity (in terms of affordability for those in poverty).

Significant changes in the food system require them to be acceptable to the public ('public license'), or they will be rejected. Focus groups with members of the public around the world, on the issue of changing diets, have shown that there is a general belief that the government plays a key role in leading efforts for change in consumption patterns (Wellesley et al. 2015). If governments are not leading on an issue, or indicating the need for it through leading public dialogue, it signals to their citizens that the issue is unimportant or undeserving of concern.

In summary, there is significant potential (*high confidence*) that, through aligning multiple policy goals, multiple benefits can be realised that positively impact public health, mitigation and adaptation (e.g., adoption of healthier diets, reduction in waste, reduction in environmental impact). These benefits may not occur without the alignment across multiple policy areas (*high confidence*).

5.7.2 Enablers for changing markets and trade

'Demand' for food is not an exogenous variable to the food system but is shaped crucially by its ability to produce, market, and supply food of different types and prices. These market dynamics can be influenced by a variety of factors beyond consumer preferences (e.g., corporate power and marketing, transparency, the food environment more generally), and the ability to reshape the market can also depend on its internal resilience and/or external shocks (Challinor et al. 2018; Oliver et al. 2018).

5.7.2.1 Capital markets

Two areas are often discussed regarding the role of capital markets in shaping the food system. First, investment in disruptive technologies might stimulate climate-smart food systems (WEF/McKinsey & Company 2018 and Bailey and Wellesley 2017), including alternative proteins, such as laboratory or 'clean meat' (which has significant ability to impact on land-use requirements) (Alexander et al. 2017) (Section 5.5.1.6). An innovation environment through which disruptive technology can emerge typically requires the support of public policy, whether in directly financing small and emerging enterprises, or funding research and development via reducing tax burdens.

Second, widespread adoption of (and perhaps underpinned by regulation for) natural capital accounting as well as financial accounting are needed. Investors can then be aware of the risk exposure of institutions, which can undermine sustainability through externalising costs onto the environment. The prime example of this in the realm of climate change is the Carbon Disclosure Project, with around 2500 companies voluntarily disclosing their carbon footprint, representing nearly 60% of the world's market capital (CDP 2018).

5.7.2.2 Insurance and re-insurance

The insurance industry can incentivise actors' behaviour towards greater climate mitigation or adaptation, including building resilience. For example, Lloyd's of London analysed the implications of extreme weather for the insurance market, and conclude that the insurance industry needs to examine their exposure to risks through the food supply chain and develop innovative risk-sharing products that can make an important contribution to resilience of the global food system (Lloyd's 2015).

Many of these potential areas for enabling healthy and sustainable food systems are also knowledge gaps, in that, whilst the levers are widely known, their efficacy and the ability to scale-up, in any given context, are poorly understood.

5.7.3 Just Transitions to sustainability

Research is limited on how land-use transitions would proceed from ruminant production to other socio-ecological farming systems. Ruminants have been associated with humans since the early development of agriculture, and the role of ruminants in many agricultural systems and smallholder communities is substantial. Ruminant production systems have been adapted to a wide range of socioeconomic and environmental conditions in crop, forestry, and food processing settings (Čolović et al. 2019), bioenergy production (de Souza et al. 2019), and food waste recycling (Westendorf 2000). Pasture cultivation in succession to crops is recognised as important to management of pest and diseases cycles and to improve soil carbon stocks and soil quality (Carvalho and Dedieu 2014). Grazing livestock is important as a reserve of food and economic stocks for some smallholders (Ouma et al. 2003).

Possible land-use options for transitions away from livestock production in a range of systems include (a) retain land but reduce investments to run a more extensive production system; (b) change land use by adopting a different production activity; (c) abandon land (or part of the farm) to allow secondary vegetation regrowth (Carvalho et al. 2019 and Laue and Arima 2016); and (d) invest in afforestation or reforestation (Baynes et al. 2017). The extensification option could lead to increases rather than decreases in GHG emissions related to reduction in beef consumption. Large-scale abandonment, afforestation, or reforestation would probably have more positive environmental outcomes, but could result in economic and social issues that would require governmental subsidies to avoid decline and migration in some regions (Henderson et al. 2018).

Alternative economic use of land, such as bioenergy production, could balance the negative socioeconomic impact of reducing beef output, reduce the tax values needed to reduce consumption, and avoid extensification of ruminant production systems (Wirsenius et al. 2011). However, the analysis of the transition of land use for ruminants to other agricultural production systems is still a literature gap (Cross-Chapter Box 7 in Chapter 6).

Finally, it is important to recognise that, while energy alternatives produce the same function for the consumer, it is questionable that providing the same nutritional value through an optimised mix of dietary ingredients provides the same utility for humans. Food has a central role in human pleasure, socialisation, cultural identity, and health (Röös et al. 2017), including some of the most vulnerable groups, so Just Transitions and their costs need to be taken into account. Pilot projects are important to provide greater insights for large-scale policy design, implementation, and enforcement.

In summary, more research is needed on how land-use transitions would proceed from ruminant production to other farming systems and affect the farmers and other food system actors involved. There is *limited evidence* on what the decisions of farmers under lower beef demand would be.

5.7.4 Mobilising knowledge

Addressing climate change-related challenges and ensuring food security requires all types of knowledge (formal/non-formal, scientific/indigenous, women, youth, technological). Miles et al. (2017) stated that a research and policy feedback that allows transitions to sustainable food systems must take a whole system approach. Currently, in transmitting knowledge for food security and land sustainability under climate change there are three major approaches: (i) public technology transfer with demonstration (extension agents); (ii) public and private advisory services (for intensification techniques) and; (iii) non-formal education with many different variants such as farmer field schools, rural resource centres; facilitation extension where front-line agents primarily work as 'knowledge brokers' in facilitating the teaching-learning process among all types of farmers (including women and rural young people), or farmer-to-farmer, where farmers act themselves as knowledge transfer and sharing actors through peer processes.

5.7.4.1 Indigenous and local knowledge

Recent discourse has a strong orientation towards scaling-up innovation and adoption by local farmers. However, autonomous adaptation, indigenous knowledge and local knowledge are both important for agricultural adaptation (Biggs et al. 2013) (Section 5.3). These involve the promotion of farmer participation in governance structures, research, and the design of systems for the generation and dissemination of knowledge and technology, so that farmers' needs and knowledge can be taken into consideration. Klenk et al. (2017) found that mobilisation of local knowledge can inform adaptation decision-making and may facilitate greater flexibility in government-funded research. As an example, rural innovation in terrace agriculture developed on the basis of a local coping mechanism and adopted by peasant farmers in Latin America may serve as an adaptation option or starting place for learning about climate change responses (Bocco and Napoletano 2017). Clemens et al. (2015) found that an open dialogue platform enabled horizontal exchange of ideas and alliances for social learning and knowledge-sharing in Vietnam. Improving local technologies in a participatory manner, through on-farm experimentation, farmer-to-farmer exchange, consideration of women and youths, is also relevant in mobilising knowledge and technologies.

5.7.4.2 Citizen science

Citizen science has been tested as a useful tool with potential for biodiversity conservation (Schmitz et al. 2015) and mobilising knowledge from society. In food systems, knowledge-holders (e.g., farmers and pastoralists) are trained to gather scientific data in order to promote conservation and resource management (Fulton et al. 2019) or to conserve and use traditional knowledge in developed countries relevant to climate change adaptation and mitigation through the use of ICT (Calvet-Mir et al. 2018).

5.7.4.3 Capacity building and education

Mobilising knowledge may also require significant efforts on capacity building and education to scale up food system responses to climate change. This may involve increasing the capacity of farmers to manage current climate risks and to mitigate and adapt in their local contexts, and of citizens and consumers to understand the links between food demand and climate change emissions and impacts, as well as policy makers to take a systemic view of the issues. Capacity building may also require institutional change. For example, alignment of policies towards sustainable and healthy food systems may require building institutional capacity across policy silos.

As a tool for societal transformation, education is a powerful strategy to accelerate changes in the way we produce and consume food. Education refers to early learning and lifelong acquisition of skills for higher awareness and actions for solving food system challenges (FAO 2005). Education also entails vocational training, research and institutional strengthening (Hollinger 2015). Educational focus changes according to the supply side (e.g., crop selection, input resource management, yield improvement, and diversification) and the demand since (nutrition and dietary health implications). Education on food loss and waste spans both the supply and demand sides.

In developing countries, extension learning such as farmer field schools – also known asrural resources centers – are established to promote experiential learning on improved production and food transformation (FAO 2016c). In developed countries, education campaigns are being undertaken to reduce food waste, improve diets and redefine acceptable food (e.g., "less than perfect" fruits and vegetables), and ultimately can contribute to changes in the structure of food industries (Heller 2019; UNCCD 2017).

The design of new education modules from primary to secondary to tertiary education could help create new jobs in the realm of sustainability (e.g., certification programmes). For example, one area could be educating managers of recycling programmes for food-efficient cities where food and organic waste are recycled to become fertilisers (Jara-Samaniego et al. 2017). Research and education need to be coordinated so that knowledge gaps can be filled and greater trust established in shifting behaviour of individuals to be more sustainable. Education campaigns can also influence policy and legislation, and help to advance successful outcomes for climate change mitigation and adaptation regarding supply-side innovations, technologies, trade, and investment, and demand-side evolution of food choices for health and sustainability, and greater gender equality throughout the entire food system (Heller 2019).

5.7.5 Knowledge gaps and key research areas

Knowledge gaps around options and solutions and their (co-)benefits and trade-offs are increasingly important now that implementation of mitigation and adaptation measures is scaling up.

Research is needed on how a changing climate and interventions to respond to it will affect all aspects of food security, including access, utilisation and stability, not just availability. Knowledge gaps across all the food security pillars are one of the barriers hindering mitigation and adaptation to climate change in the food system and its capacity to deliver food security. The key areas for climate change, food systems, and food security research are enlisted below.

5.7.5.1 Impacts and adaptation

Climate Services (food availability). Agriculture and food security is a priority area for the Global Framework for Climate Services (GFCS) a programme of the World Meteorological Organization (WMO). The GFCS enables vulnerable sectors and populations to better manage climate variability and adapt to climate change (Hansen et al. 2018). Global precipitation datasets and remote sensing technologies can be used to detect local to regional anomalies in precipitation as a tool for devising early-warning systems for drought-related impacts, such as famine (Huntington et al. 2017).

Crop and livestock genetics (food availability, utilisation). Advances in plant breeding are crucial for enhancing food security under changing climate for a wide variety of crops including fruits and vegetables as well as staples. Genetics improvement is needed in order to breed crops and livestock that can both reduce GHG emissions, increase drought and heat tolerance (e.g., rice), and enhance nutrition and food security (Nankishore and Farrell 2016; Kole et al. 2015). Many of these characteristics already exist in traditional varieties, including orphan crops and indigenous and local breeds, so research is needed to recuperate such varieties and evaluate their potential for adaptation and mitigation.

Phenomics-assisted breeding appears to be a promising tool for deciphering the stress responsiveness of crop and animal species (Papageorgiou 2017; Kole et al. 2015; Lopes et al. 2015; Boettcher et al. 2015). Initially discovered in bacteria and archaea, CRISPR–Cas9 is an adaptive immune system found in prokaryotes and since 2013 has been used as a genome editing tool in plants. The main use of CRISPR systems is to achieve improved yield performance, biofortification, biotic and abiotic stress tolerance, with rice (Oryza sativa) being the most studied crop (Gao 2018 and Ricroch et al. 2017).

Climate impact models (food availability). Understanding the full range of climate impacts on staple crops (especially those important in developing countries, such as fruits and vegetables) is missing in the current climate impact models. Further, the CO_2 effects on nutrition quality of different crops are just beginning to be parameterised in the models (Müller et al. 2014). Bridging these gaps is essential for projecting future dietary diversity, healthy diets, and food security (Bisbis et al. 2018). Crop model improvements are needed for simulation of evapotranspiration to guide crop water management in future climate conditions (Cammarano et al. 2016). Similarly, mores studies are needed to understand the impacts of climate change on global rangelands, livestock and aquaculture, which have received comparatively less attention than the impacts on crop production.

Resilience to extreme events (food availability, access, utilisation, and stability). On the adaptation side, knowledge gaps include impacts of climate shocks (Rodríguez Osuna et al. 2014) as opposed to impacts of slow-onset climate change, how climate-related harvest failures in one continent may influence food security outcomes in others, impacts of climate change on fruits and vegetables and their nutrient contents.

5.7.5.2 Emissions and mitigation

GHG emissions inventory techniques (food utilisation). Knowledge gaps include food consumption-based emissions at national scales, embedded emissions (overseas footprints) of food systems, comparison of GHG emissions per type of food systems (e.g., smallholder and large-scale commercial food systems), and GHG emissions from land-based aquaculture. An additional knowledge gap is the need for more socio-economic assessments of the potential of various integrated practices to deliver the mitigation potential estimated from a biophysical perspective. This needs to be effectively monitored, verified, and implemented, once barriers and incentives to adoption of the techniques, practices, and technologies are considered. Thus, future research needs fill the gaps on evaluation of climate actions in the food system.

Food supply chains (food availability). The expansion of the cold chain into developing economies means increased energy consumption and GHG emissions at the consumer stages of the food system, but its net impact on GHG emissions for food systems as a whole, is complex and uncertain (Heard and Miller 2016). Further understanding of negative side effects in intensive food processing systems is still needed.

Blockchains, as a distributed digital ledger technology which ensures transparency, traceability, and security, is showing promise for easing some global food supply chain management challenges, including the need for documentation of sustainability and the circular economy for stakeholders including governments, communities, and consumers to meet sustainability goals. Blockchain-led transformation of food supply chains is still in its early stages; research is needed on overcoming barriers to adoption (Tripoli and Schmidhuber 2018; Casado-Vara et al. 2018; Mao et al. 2018; Saberi et al. 2019).

5.7.5.3 Synergies and trade-offs

Supply-side and demand-side mitigation and adaptation (food availability, utilisation). Knowledge gaps exist in characterising the potential and risks associated with novel mitigation technologies on the supply side (e.g., inhibitors, targeted breeding, cellular agriculture, etc.). Additionally, most integrated assessment models (IAMs) currently have limited regional data on BECCS projects because of little BECCS implementation (Lenzi et al. 2018). Hence, several BECCS scenarios rely on assumptions regarding regional climate, soils and infrastructure suitability (Köberle et al. 2019) as well as international trade (Lamers et al. 2011).

Areas for study include how to incentivise, regulate, and raise awareness of the co-benefits of healthy consumption patterns and climate change mitigation and adaptation; to improve access to healthy diets for vulnerable groups through food assistance programmes; and to implement policies and campaigns to reduce food loss and food waste. Knowledge gaps also exist on the role of different policies, and underlying uncertainties, to promote changes in food habits towards climate resilience and healthy diets.

Food systems, land-use change, and telecoupling (food availability, access, utilisation). The analytical framework of telecoupling has recently been proposed to address this complexity, particularly the connections, flows, and feedbacks characterising food systems (Friis et al. 2016; Easter et al. 2018). For example, how will climate-induced shifts in livestock and crop diseases affect food production and consumption in the future. Investigating the social and ecological consequences of these changes will contribute to decision-making under uncertainty in the future. Research areas include food systems and their boundaries, hierarchies, and scales through metabolism studies, political ecology and cultural anthropology.

Food-Energy-Water Nexus (food availability, utilisation, stability). Emerging interdisciplinary science efforts are providing new understanding of the interdependence of food, energy, and water systems. These interdependencies are beginning to take into account climate change, food security, and AFOLU assessments (Scanlon et al. 2017; Liu et al. 2017). These science advances, in turn, provide critical information for coordinated management to improve the affordability, reliability, and environmental sustainability of food, energy, and water systems. Despite significant advances within the past decade, there are still many challenges for the scientific community. These include the need for interdisciplinary science related to the food-energy-water nexus; ground-based monitoring and modelling at local-to-regional scales (Van Gaelen et al. 2017); incorporating human and institutional behaviour in models; partnerships among universities, industry, and government to develop policy-relevant data; and systems modelling to evaluate trade-offs associated with food-energy-water decisions (Scanlon et al. 2017).

However, the nexus approach, as a conceptual framework, requires the recognition that, although land and the goods and services it provides is finite, potential demand for the goods and services may be greater than the ability to supply them sustainably (Benton et al. 2018). By addressing demand-side issues, as well as supply-side efficiencies, it provides a potential route for minimising trade-offs for different goods and services (Benton et al. 2018) (Section 5.6).

5.8 Future challenges to food security

A particular concern in regard to the future of food security is the potential for the impacts of increasing climate extremes on food production to contribute to multi-factored complex events such as food price spikes. In this section, we assess literature on food price spikes and potential strategies for increasing resilience to such occurrences. We then assess the potential for such food system events to affect migration and conflict.

5.8.1 Food price spikes

Under average conditions, global food system markets may function well, and equilibrium approaches can estimate demand and supply with some confidence; however, if there is a significant shock, the market can fail to smoothly link demand and supply through price, and a range of factors can act to amplify the effects of the shock, and transmit it across the world (Box 5.5). Given the potential for shocks driven by changing patterns of extreme weather to increase with climate change, there is the potential for market volatility to disrupt food supply through creating food price spikes. This potential is exacerbated by the interconnectedness of the food system (Puma et al. 2015) with other sectors (i.e., the food system depends on water, energy, and transport) (Homer-Dixon et al. 2015), so the impact of shocks can propagate across sectors and geographies (Homer-Dixon et al. 2015). There is also less spare land globally than there has been in the past, such that if prices spike, there are fewer options to bring new production on stream (Marianela et al. 2016).

Increasing extreme weather events can disrupt production and transport logistics. For example, in 2012 the USA Corn Belt suffered a widespread drought; USA corn yield declined 16% compared to 2011 and 25% compared to 2009. In 2016, a record yield loss in France that is attributed to a conjunction of abnormal warmness in late autumn and abnormal wet in the following spring (Ben-Ari et al. 2018) is another well-documented example. To the extent that such supply shocks are associated with climate change, they may become more frequent and contribute to greater instability in agricultural markets in the future.

Furthermore, analogue conditions of past extremes might create significantly greater impacts in a warmer world. A study simulating analogous conditions to the Dust Bowl drought in today's agriculture suggests that Dust Bowl-type droughts today would have unprecedented consequences, with yield losses about 50% larger than the severe drought of 2012 (Glotter and Elliott 2016). Damages at these extremes are highly sensitive to temperature, worsening by about 25% with each degree centigrade of warming. By mid-century, over 80% of summers are projected to have average temperatures that are likely to exceed the hottest summer in the Dust Bowl years (1936) (Glotter and Elliott 2016).

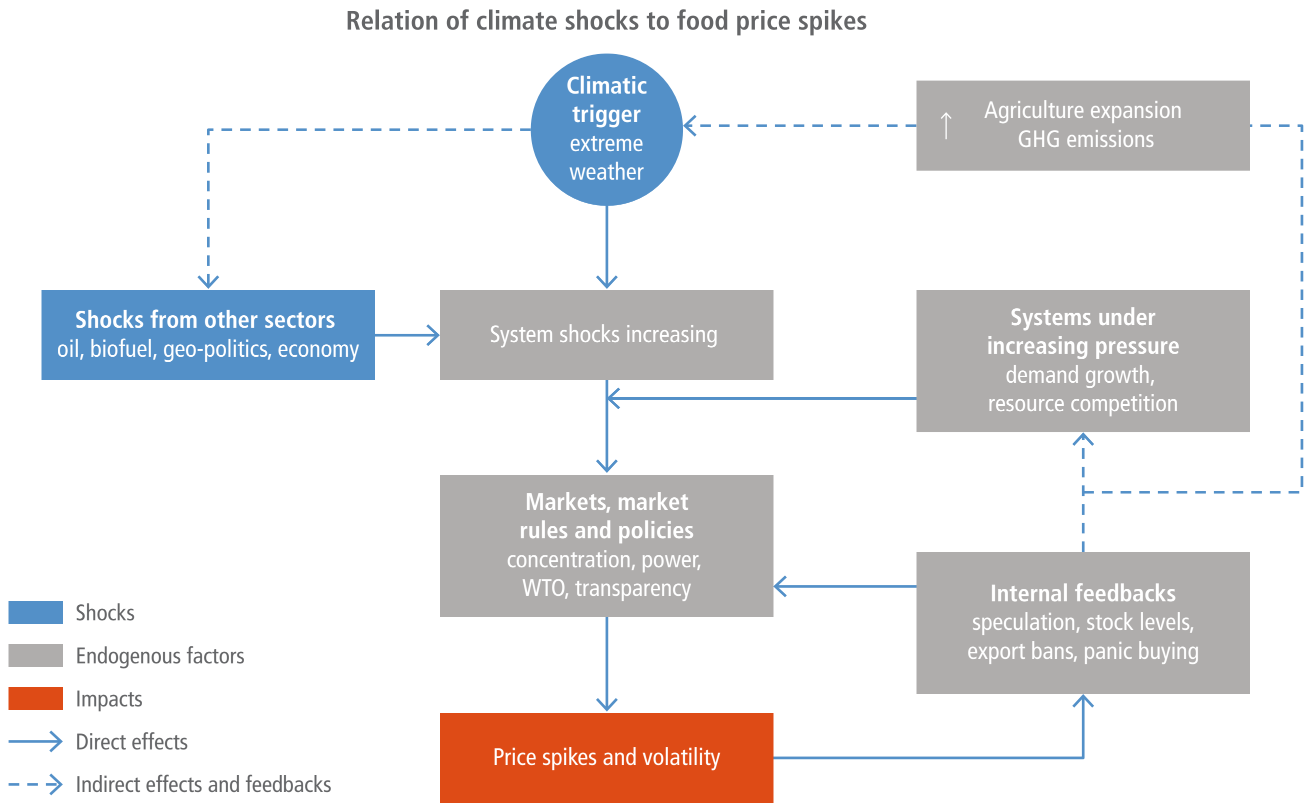


Figure 5.17 | Underlying processes that affect the development of a food price spike in agricultural commodity markets (Challinor et al. 2018).

How a shortfall in production – or an interruption in trade due to an event affecting a logistics choke-point (Wellesley et al. 2017) – of any given magnitude may create impacts depends on many interacting factors (Homer-Dixon et al. 2015; Tadasse et al. 2016; Challinor et al. 2018). The principal route is by affecting agricultural commodity markets, which respond to a perturbation through multiple routes as in Figure 5.17. This includes pressures from other sectors (such as, if biofuels policy is incentivising crops for the production of ethanol, as happened in 2007–2008). The market response can be amplified by poor policies, setting up trade and non-trade barriers to exports, from countries seeking to ensure their local food security (Bailey et al. 2015). Furthermore, the perception of problems can fuel panic buying on the markets that in turn drives up prices.

Thus, the impact of an extreme weather event on markets has both a *trigger* component (the event) and a risk *perception* component (Challinor et al. 2016, 2018). Through commodity markets, prices change across the world because almost every country depends, to a greater or lesser extent, on trade to fulfil local needs. Commodity prices can also affect local market prices by altering input prices, changing the cost of food aid, and through spill-over effects. For example, in 2007–2008 the grain affected by extreme weather was wheat, but there was a significant price spike in rice markets (Dawe 2010).

As discussed by Bailey et al. (2015), there are a range of adaptation measures that can be put in place to reduce the impact of climate-related production shortfalls. These include (i) ensuring transparency of public and private stocks, as well as improved seasonal forecasting to signal forthcoming yield shortfalls (FAO 2016a; Ceglar et al. 2018; Iizumi et al. 2018), (ii) building real or virtual stockholdings, (iii) increasing local productivity and diversity (as a hedge against a reliance on trade) and (iv) ensuring smoother market responses, through, for example, avoiding the imposition of export bans.

In summary, given the likelihood that extreme weather will increase, in both frequency and magnitude (Hansen et al. 2012; Coumou et al. 2014; Mann et al. 2017; Bailey et al. 2015), and the current state of global and cross-sectoral interconnectedness, the food system is at increasing risk of disruption (*medium evidence, medium agreement*), with large uncertainty about how this could manifest. There is, therefore, a need to build resilience into international trade as well as local supplies.

Box 5.5 | Market drivers and the consequences of extreme weather in 2010–2011

The 2010–2011 food price spike was initially triggered by the exceptional heat in summer 2010, with an extent from Europe to the Ukraine and Western Russia (Barriopedro et al. 2011; Watanabe et al. 2013; Hoag 2014). The heatwave in Russia was extreme in both temperature (over 40°C) and duration (from July to mid-August in 2010). This reduced wheat yields by approximately one third (Wegren 2011; Marchand et al. 2016). Simultaneously, in the Indus Valley in Pakistan, unprecedented rainfall led to flooding, affecting the lives and livelihoods of 20 million people. There is evidence that these effects were both linked and made more likely through climate change (Mann et al. 2017).

In response to its shortfall in yields, Russia imposed an export ban in order to maintain local food supplies. Other countries responded in a largely uncoordinated ways, each of them driven by internal politics as well as national self-interests (Jones and Hiller 2017). Overall, these measures led to rapid price rises on the global markets (Welton 2011), partly through panic buying, but also through financial speculation (Spratt 2013).

Analysis of responses to higher food prices in the developing world showed that lower-income groups responded by taking on more employment, reducing food intake, limiting expenditures, spending savings (if available), and participating in demonstrations. People often identified their problems as stemming from collusion between powerful incumbent interests (e.g., of politicians and big business) and disregard for the poor (Hossain and Green 2011). This politicised social response helped spark food-related civil protest, including riots, across a range of countries in 2010–2011 (Natalini et al. 2017). In Pakistan, food price rises were exacerbated by the economic impacts of the floods, which further contributed to food-related riots in 2010.

Price spikes also impact on food security in the developed world. In the UK, global commodity price inflation influenced local food prices, increasing food-price inflation by about five times at the end of 2010. Comparing household purchases over the five-year period from 2007 to 2011 showed that the amount of food bought declined, on average, by 4.2%, whilst paying 12% more for it. The lowest income decile spent 17% more by 2011 than they did in 2007 (Holding et al. 2013; Tadasse et al. 2016). Consumers also saved money by trading down for cheaper alternatives. For the poorest, in the extreme situation, food became unaffordable: the Trussell Trust, a charity supplying emergency food handouts for people in crisis, noted a 50% increase in handouts in 2010.

5.8.2 Migration and conflict

Since the IPCC AR5 (Porter et al. 2014; Cramer et al. 2014), new work has advanced multi-factor methodological issues related to migration and conflict (e.g., Kelley et al. 2015, 2017; Werrell et al. 2015; Challinor et al. 2018; Pasini et al. 2018). These in particular have addressed systemic risks to food security that result from cascading impacts triggered by droughts and floods and how these are related to a broad range of societal influences.

Climate variability and extremes have short-, medium – and long-term impacts on livelihoods and livelihood assets – especially of the poor – contributing to greater risk of food insecurity and malnutrition (FAO et al. 2018). Drought threatens local food security and nutrition and aggravates humanitarian conditions, which can trigger large-scale human displacement and create a breeding ground for conflict (Maystadt and Ecker 2014). There is *medium agreement* that existing patterns of conflict could be reinforced under climate change, affecting food security and livelihood opportunities, for example, in already fragile regions with ethnic divides such as North and Central Africa as well as Central Asia (Buhaug 2016; Schleussner et al. 2016) (Box 5.6).

Challinor et al. (2018) have developed a typology for transboundary and transboundary risk transmission that distinguishes the roles of climate and social and economic systems. To understand these complex interactions, they recommend a combination of methods that include expert judgement; interactive scenario building; global systems science and big data; and innovative use of climate and integrated assessment models; and social science techniques (e.g., surveys, interviews, and focus groups).

5.8.2.1 Migration

There has been a surge in international migration in recent years, with around five million people migrating permanently in 2016 (OECD 2017). Though the initial driver of migration may differ across populations, countries and contexts, migrants tend to seek the same fundamental objective: to provide security and adequate living conditions for their families and themselves. Food insecurity is a critical ‘push’ factor driving international migration, along with conflict, income inequality, and population growth. The act of migration itself causes food insecurity, given the lack of income opportunities and adverse conditions compounded by conflict situations.

Warner et al. (2012) found the interrelationships between changing rainfall patterns, food and livelihood security in eight countries in Asia, Africa and Latin America. Several studies in Africa have found that persistent droughts and land degradation contributed to both seasonal and permanent migration (Gray 2011; Gray and Mueller 2012; Hummel 2015; Henry et al. 2004; Folami and Folami 2013), worsening the vulnerability of different households (Dasgupta et al. 2014).

Box 5.6 | Migration in the Pacific region: Impacts of climate change on food security

Climate change-induced displacement and migration in the Pacific has received wide attention in the scientific discourse (Fröhlich and Klepp 2019). The processes of climate change and their effects in the region have serious implications for Pacific Island nations as they influence the environments that are their 'life-support systems' (Campbell 2014). Climate variability poses significant threats to both agricultural production and food security. Rising temperatures and reductions in groundwater availability, as well as increasing frequency and severity of disaster events translate into substantial impacts on food security, causing human displacement, a trend that will be aggravated by future climate impacts (ADB 2017). Declining soil productivity, groundwater depletion, and non-availability of freshwater threatens agricultural production in many remote atolls.

Many countries in the Pacific devote a large share of available land area to agricultural production. For example, more than 60% of land area is cultivated in the Marshall Islands and Tuvalu and more than 40% in Kiribati and Tonga. With few options to expand agricultural area, the projected impacts of climate change on food production are of particular concern (ADB 2013, 2017). The degradation of available land area for traditional agriculture, adverse disruptions of agricultural productivity and diminishing livelihood opportunities through climate change impacts leads to increasing poverty and food insecurity, incentivising migration to urban agglomerations (ADB 2017; FAO et al. 2018).

Campbell (2014) describe the trends that lead to migration. First, climate change, including rising sea levels, affects communities' land security, which is the physical presence on which to live and sustain livelihoods. Second, they impinge on livelihood security (especially food security) of island communities where the productivity of both subsistence and commercial food production systems is reduced. Third, the effects of climate change are especially severe on small-island environments since they result in declining ecological habitat. The effects on island systems are mostly manifested in atolls through erosion and inundation, and on human populations through migration. Population growth and scenarios of climate change are *likely* to further induce food stress as impacts unfold in the coming decades (Campbell 2015).

While the populations of several islands and island groups in the Pacific (e.g., Tuvalu, Carteret Islands, and Kiribati) have been perceived as the first probable victims of rising seas so that their inhabitants would become, and in some quarters already are seen to be, the first 'environmental' or 'climate change refugees', migration patterns vary. Especially in small islands, the range and nature of the interactions among economic, social, and/or political drivers are complex. For example, in the Maldives, Stojanov et al. (2017) show that while collective perceptions support climate change impacts as being one of the key factors prompting migration, individual perceptions give more credence to other cultural, religious, economic or social factors.

In the Pacific, Tuvalu has long been a prime candidate to disappear due to rising sea levels, forcing human migration. However, results of a recent study (Kench et al. 2018) challenge perceptions of island loss in Tuvalu, reporting that there is a net increase in land area of 73.5 ha. The findings suggest that islands are dynamic features likely to persist as habitation sites over the next century, presenting opportunities for adaptation that embrace the heterogeneity of island types and processes. Farbotko (2010) and Farbotko and Lazrus (2012) present Tuvalu as a site of 'wishful sinking', in the climate change discourse. These authors argue that representations of Tuvalu as a laboratory for global climate change migration are visualisations by non-locals.

In Nanumea (Tuvalu), forced displacements and voluntary migrations are complex decisions made by individuals, families and communities in response to discourses on risk, deteriorating infrastructure and other economic and social pressures (Marino and Lazrus 2015). In many atoll nations in the Western Pacific, migration has increasingly become a sustainable livelihood strategy, irrespective of climate change (Connell 2015).

In Lamen Bay, Vanuatu, migration is both a cause and consequence of local vulnerabilities. While migration provides an opportunity for households to meet their immediate economic needs, it limits the ability of the community to foster longer-term economic development. At the same time, migration adversely affects the ability of the community to maintain food security due to lost labour and changing attitudes towards traditional ways of life among community members (Craven 2015).

Dependency on rainfed agriculture ranges from 13% in Mexico to more than 30% in Guatemala, Honduras, and Nicaragua, suggesting a high degree of sensitivity to climate variability and change, and undermined food security (Warner et al. 2009). Studies have demonstrated that Mexican migration (Feng et al. 2010; Nawrotzki et al. 2013) and Central American migration (WFP 2017) fluctuate in response to climate variability. The food system is heavily dependent on maize and bean production and long-term climate change and variability significantly affect the productivity of these crops and the livelihoods of smallholder farmers (WFP 2017). In rural Ecuador, adverse environmental conditions prompt out-migration, although households respond to these challenges in diverse ways resulting in complex migratory responses (Gray and Bilsborrow 2013).

Migration patterns have been linked to heat stress in Pakistan (Mueller et al. 2014) and climate variability in the Sundarbans due to decline in food security (Guha and Roy 2016). In Bangladesh, the impacts of climate change have been on the rise throughout the last three decades with increasing migration, mostly of men leaving women and children to cope with increasing effects of natural disasters (Rabbani et al. 2015).

Small islands are very sensitive to climate change impacts (*high confidence*) (Nurse et al. 2014) and impacted by multiple climatic stressors (IPCC 2018a and SROCC). Food security in the Pacific, especially in Micronesia, has worsened in the past half century and climate change is *likely* to further hamper local food production, especially in low-lying atolls (Connell 2016). Migration in small islands (internally and internationally) occurs for multiple reasons and purposes, mostly for better livelihood opportunities (*high confidence*).

Beyond rising sea levels, the effects of increasing frequency and intensity of extreme events such as severe tropical cyclones are *likely* to affect human migration in the Pacific (Connell 2015; Krishnapillai and Gavenda 2014; Charan et al. 2017; Krishnapillai 2017). On Yap Island, extreme weather events are affecting every aspect of atoll communities' existence, mainly due to the islands' small size, their low elevation, and extensive coastal areas (Krishnapillai 2018). Displaced atoll communities on Yap Island grow a variety of nutritious vegetables and use alternative crop production methods such as small-plot intensive farming, raised bed gardening, as part of a community-based adaptation programme (Krishnapillai and Gavenda 2014; Krishnapillai 2018).

Recurrences of natural disasters and crises threaten food security through impacts on traditional agriculture, causing the forced migration and displacement of coastal communities to highlands in search of better living conditions. Although considerable differences occur in the physical manifestations of severe storms, such climate stressors threaten the life-support systems of many atoll communities (Campbell et al. 2014). The failure of these systems resulting from climate disasters propel vulnerable atoll communities into poverty traps, and low adaptive capacity could eventually force these communities to migrate.

5.8.2.2 Conflict

While climate change will not alone cause conflict, it is often acknowledged as having the potential to exacerbate or catalyse conflict in conjunction with other factors. Increased resource competition can aggravate the potential for migration to lead to conflict. When populations continue to increase, competition for resources will also increase, and resources will become even scarcer due to climate change (Hendrix and Glaser 2007). In agriculture-dependent communities in low-income contexts, droughts have been found to increase the likelihood of violence and prolonged conflict at the local level, which eventually pose a threat to societal stability and peace (FAO et al. 2017). In contrast, conflicts can also have diverging effects on agriculture due to land abandonment, resulting in forest growth, or agriculture expansion causing deforestation, for example, in Colombia (Landholm et al. 2019).

Several studies have explored the causal links among climate change, drought, impacts on agricultural production, livelihoods, and civil unrest in Syria from 2007–2010, but without agreement as to the role played by climate in subsequent migration (Kelley et al. 2015, 2017; Challinor et al. 2018; Selby et al. 2017; Hendrix 2018). Contributing factors that have been examined include rainfall deficits, population growth, agricultural policies, and the influx of refugees that had placed burdens on the region's water resources (Kelley et al. 2015). Drought may have played a role as a trigger, as this drought was the longest and the most intense in the last 900 years (Cook et al. 2016; Mathbout et al. 2018). Some studies linked the drought to widespread crop failure, but the climate hypothesis has been contested (Selby et al. 2017; Hendrix 2018). Recent evidence shows that the severe drought triggered agricultural collapse and displacement of rural farm families, with approximately 300,000 families going to Damascus, Aleppo and other cities (Kelley et al. 2017).

Persistent drought in Morocco during the early 1980s resulted in food riots and contributed to an economic collapse (El-Said and Harrigan 2014). A drought in Somalia that fuelled conflict through livestock price changes, establishing livestock markets as the primary channel of impact (Maystadt and Ecker 2014). Cattle raiding as a normal means of restocking during drought in the Great Horn of Africa led to conflict (ICPAC and WFP 2017) whereas a region-wide drought in northern Mali in 2012 wiped out thousands of livestock and devastated the livelihoods of pastoralists, in turn swelling the ranks of armed rebel factions and forcing others to steal and loot for survival (Breisinger et al. 2015).

On the other hand, inter-annual adjustments in international trade can play an important role in shifting supplies from food surplus regions to regions facing food deficits which emerge as a consequence of extreme weather events, civil strife, and/or other disruptions (Baldos and Hertel 2015). A more freely functioning global trading system is tested for its ability to deliver improved long run food security in 2050.

In summary, given increasing extreme events and global and cross-sectoral interconnectedness, the food system is at increasing risk of disruption, for example, via migration and conflict (*high confidence*). {5.2.3, 5.2.4}

Frequently Asked Questions

FAQ 5.1 | How does climate change affect food security?

Climate change negatively affects all four pillars of food security: availability, access, utilisation and stability. Food availability may be reduced by negative climate change impacts on productivity of crops, livestock and fish, due, for instance, to increases in temperature and changes in rainfall patterns. Productivity is also negatively affected by increased pests and diseases, as well as changing distributions of pollinators under climate change. Food access and its stability may be affected through disruption of markets, prices, infrastructure, transport, manufacture, and retail, as well as direct and indirect changes in income and food purchasing power of low-income consumers. Food utilisation may be directly affected by climate change due to increases in mycotoxins in food and feed with rising temperatures and increased frequencies of extreme events, and indirectly through effects on health. Elevated atmospheric CO_2 concentrations can increase yields at lower temperature increases, but tend to decrease protein content in many crops, reducing their nutritional values. Extreme events, for example, flooding, will affect the stability of food supply directly through disruption of transport and markets.

FAQ 5.2 | How can changing diets help address climate change?

Agricultural activities emit substantial amounts of greenhouse gases (GHGs). Food supply chain activities past the farm gate (e.g., transportation, storage, packaging) also emit GHGs, for instance due to energy use. GHG emissions from food production vary across food types. Producing animal-sourced food (e.g., meat and dairy) emits larger amount of GHGs than growing crops, especially in intensive, industrial livestock systems. This is mainly true for commodities produced by ruminant livestock such as cattle, due to enteric fermentation processes that are large emitters of methane. Changing diets towards a lower share of animal-sourced food, once implemented at scale, reduces the need to raise livestock and changes crop production from animal feed to human food. This reduces the need for agricultural land compared to present and thus generates changes in the current food system. From field to consumer this would reduce overall GHG emissions. Changes in consumer behaviour beyond dietary changes, such as reduction of food waste, can also have, at scale, effects on overall GHG emissions from food systems. Consuming regional and seasonal food can reduce GHG emissions, if they are grown efficiently.

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