

## Chapter 5: Food Security

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## 1 **Executive summary**

2 **The current food system (production, transport, processing, packaging, storage, retail,**  
3 **consumption, loss and waste) feeds the great majority of world population and supports the**  
4 **livelihoods of ca. 200 million people.** Since 1961, food supply per capita has increased more than  
5 30%, accompanied by greater use of nitrogen fertilisers (increase of about 800%) and water resources  
6 for irrigation (increase of more than 100%). However, an estimated 821 million people are currently  
7 undernourished, 151 million children under 5 are stunted, 613 million women and girls aged 15 to 49  
8 suffer from iron deficiency, and 2 billion adults are overweight or obese. The food system is under  
9 pressure from non-climate stressors (e.g., population and income growth, demand for animal-sourced  
10 products), and from climate change. These climate and non-climate stresses are impacting the four  
11 pillars of food security (availability, access, utilisation, and stability). {5.1.1, 5.1.2}

12 **Observed climate change is already affecting food security through increasing temperatures,**  
13 **changing precipitation patterns, and greater frequency of some extreme events (*high***  
14 ***confidence*).** Increasing temperatures are affecting agricultural productivity in higher latitudes, raising  
15 yields of some crops (maize, cotton, wheat, sugar beets), while yields of others (maize, wheat, barley)  
16 are declining in lower-latitude regions. Warming compounded by drying has caused yield declines in  
17 parts of Southern Europe. Based on indigenous and local knowledge, climate change is affecting food  
18 security in drylands, particularly those in Africa, and high mountain regions of Asia and South  
19 America. {5.2.2}

20 **Food security will be increasingly affected by projected future climate change (*high confidence*).**  
21 Across SSPs 1, 2, and 3, global crop and economic models projected a 1-29% cereal price increase in  
22 2050 due to climate change (RCP 6.0), which would impact consumers globally through higher food  
23 prices; regional effects will vary (*high confidence*). Low-income consumers are particularly at risk,  
24 with models projecting increases of 1-183 million additional people at risk of hunger across the SSPs  
25 compared to a no climate change scenario (*high confidence*). While increased CO<sub>2</sub> is projected to be  
26 beneficial for crop productivity at lower temperature increases, it is projected to lower nutritional  
27 quality (*high confidence*) (e.g., wheat grown at 546-586 ppm CO<sub>2</sub> has 5.9–12.7% less protein, 3.7–  
28 6.5% less zinc, and 5.2–7.5% less iron). Distributions of pests and diseases will change, affecting  
29 production negatively in many regions (*high confidence*). Given increasing extreme events and  
30 interconnectedness, risks of food system disruptions are growing (*high confidence*). {5.2.3, 5.2.4}

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

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

45 **Food security and climate change have strong gender and equity dimensions (*high confidence*).**  
46 Worldwide, women play a key role in food security, although regional differences exist. Climate  
47 change impacts vary among diverse social groups depending on age, ethnicity, gender, wealth, and

1 class. Climate extremes have immediate and long-term impacts on livelihoods of poor and vulnerable  
2 communities, contributing to greater risks of food insecurity that can be a stress multiplier for internal  
3 and external migration (*medium confidence*). {5.2.6} Empowering women and rights-based  
4 approaches to decision-making can create synergies among household food security, adaptation, and  
5 mitigation. {5.6.4}

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

16 **Ca. 25-30% of total GHG emissions are attributable to the food system. These are from**  
17 **agriculture and land use, storage, transport, packaging, processing, retail, and consumption**  
18 **(*medium confidence*)**. This estimate includes emissions of 10–12% from crop and livestock activities  
19 within the farm gate and 8-10% from land use and land use change including deforestation and  
20 peatland degradation (*high confidence*); 5–10% is from supply chain activities (*medium confidence*).  
21 This estimate includes GHG emissions from food loss and waste. Within the food system, during the  
22 period 2007-2016, the major sources of emissions from the supply side were agricultural production,  
23 with crop and livestock activities within the farm gate generating respectively  $142 \pm 43$  Tg CH<sub>4</sub> yr<sup>-1</sup>  
24 (*high confidence*) and  $8.3 \pm 2.3$  Tg N<sub>2</sub>O yr<sup>-1</sup> (*high confidence*), and CO<sub>2</sub> emissions linked to relevant  
25 land use change dynamics such as deforestation and peatland degradation, generating  $4.8 \pm 2.4$  Gt  
26 CO<sub>2</sub> yr<sup>-1</sup>. Using 100-year GWP values (no climate feedback) from the IPCC AR5, this implies that  
27 total GHG emissions from agriculture were  $6.2 \pm 1.9$  Gt CO<sub>2</sub>eq yr<sup>-1</sup>, increasing to  $11.0 \pm 3.1$  Gt CO<sub>2</sub>eq  
28 yr<sup>-1</sup> including relevant land use. Without intervention, these are likely to increase by about 30%–40%  
29 by 2050, due to increasing demand based on population and income growth and dietary change (*high*  
30 *confidence*). {5.4}

31 **Supply-side practices can contribute to climate change mitigation by reducing crop and**  
32 **livestock emissions, sequestering carbon in soils and biomass, and by decreasing emissions**  
33 **intensity within sustainable production systems (*high confidence*)**. Total mitigation potential of  
34 crop and livestock activities is estimated as 1.5–4.0 GtCO<sub>2</sub>-eq yr<sup>-1</sup> by 2030 at prices ranging from 20-  
35 100 USD/tCO<sub>2</sub>eq (*high confidence*). Options with large potential for GHG mitigation in cropping  
36 systems include soil carbon sequestration (at decreasing rates over time), reductions in N<sub>2</sub>O emissions  
37 from fertilisers, reductions in CH<sub>4</sub> emissions from paddy rice, and bridging of yield gaps. Options  
38 with large potential for mitigation in livestock systems include better grazing land management, with  
39 increased net primary production and soil carbon stocks, improved manure management, and higher-  
40 quality feed. Reductions in GHG emissions intensity (emissions per unit product) from livestock can  
41 support reductions in absolute emissions, provided appropriate governance to limit total production is  
42 implemented at the same time (*medium confidence*). {5.5.1}

43 **Consumption of healthy and sustainable diets presents major opportunities for reducing GHG**  
44 **emissions from food systems and improving health outcomes (*high confidence*)**. Examples of  
45 healthy and sustainable diets are high in coarse grains, pulses, fruits and vegetables, and nuts and  
46 seeds; low in energy-intensive animal-sourced and discretionary foods (such as sugary beverages);  
47 and with a carbohydrate threshold. Total mitigation potential of dietary changes is estimated as 1.8-  
48 3.4 GtCO<sub>2</sub>eq yr<sup>-1</sup> by 2050 at prices ranging from 20-100 USD/tCO<sub>2</sub> (*medium confidence*). This

1 estimate includes reductions in emissions from livestock and soil carbon sequestration on spared land,  
2 but co-benefits with health are not taken into account. Mitigation potential of dietary change may be  
3 higher, but achievement of this potential at broad scales depends on consumer choices and dietary  
4 preferences that are guided by social, cultural, environmental, and traditional factors, as well as  
5 income growth. Meat analogues such as imitation meat (from plant products), cultured meat, and  
6 insects may help in the transition to more healthy and sustainable diets, although their carbon  
7 footprints and acceptability are uncertain. {5.5.2, 5.6.5}

8 **Reduction of food loss and waste could lower GHG emissions and improve food security**  
9 **(medium confidence)**. Combined food loss and waste amount to a third of global food production  
10 **(high confidence)**. During 2010-2016, global food loss and waste equalled 8–10% of total GHG  
11 emissions from food systems **(medium confidence)**; and cost about USD 1 trillion per year (2012  
12 prices) **(low confidence)**. Technical options for reduction of food loss and waste include improved  
13 harvesting techniques, on-farm storage, infrastructure, and packaging. Causes of food loss (e.g., lack  
14 of refrigeration) and waste (e.g., behaviour) differ substantially in developed and developing  
15 countries, as well as across regions **(robust evidence, medium agreement)**. {5.5.2}

16 **Agriculture and the food system are key to global climate change responses. Combining supply-**  
17 **side actions such as efficient production, transport, and processing with demand-side**  
18 **interventions such as modification of food choices, and reduction of food loss and waste, reduces**  
19 **GHG emissions and enhances food system resilience (high confidence)**. Such combined measures  
20 can enable the implementation of large-scale land-based adaptation and mitigation strategies without  
21 threatening food security from increased competition for land for food production and higher food  
22 prices. Without combined food system measures in farm management, supply chains, and demand,  
23 adverse effects would include increased number of malnourished people and impacts on smallholder  
24 farmers **(medium evidence, high agreement)**. Just transitions are needed to address these effects. {5.5,  
25 5.6, 5.7}

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

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## 1       **5.1 Framing and context**

2       The current food system (production, transport, processing, packaging, storage, retail, consumption,  
3       loss and waste) feeds the great majority of world population and supports the livelihoods of ca. 200  
4       million people. Agriculture as an economic activity generates between 1% and 60% of national GDP  
5       in many countries, with a world average of about 4% in 2017 (World Bank 2019). Since 1961, food  
6       supply per capita has increased more than 30%, accompanied by greater use of nitrogen fertiliser  
7       (increase of about 800%) and water resources for irrigation (increase of more than 100%).

8       The rapid growth in agricultural productivity since the 1960s has underpinned the development of the  
9       current global food system that is both a major driver of climate change, and increasingly vulnerable  
10      to it (from production, transport, and market activities). Given the current food system, the FAO  
11      estimates that there is a need to produce about 50% more food by 2050 in order to feed the increasing  
12      world population (FAO 2018a). This would engender significant increases in GHG emissions and  
13      other environmental impacts, including loss of biodiversity. FAO (2018a) projects that by 2050  
14      cropland area will increase 90-325 Mha, between 6-21% more than the 1,567 Mha cropland area of  
15      2010, depending on climate change scenario and development pathway (the lowest increase arises  
16      from reduced food loss and waste and adoption of more sustainable diets).

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

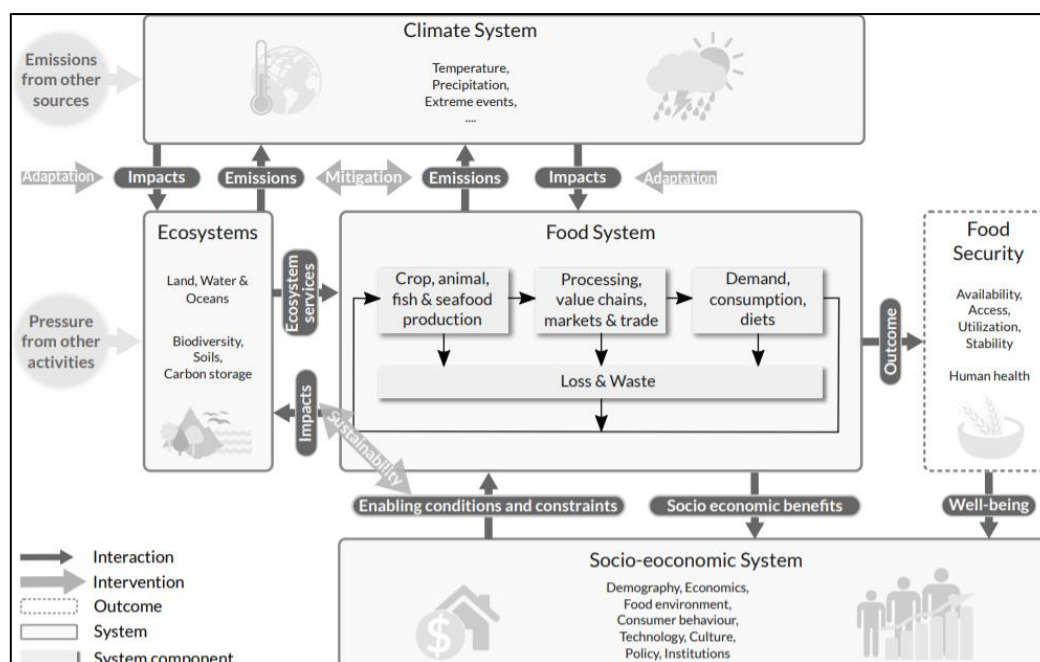
22      Using a food system approach, this chapter addresses how climate change affects food security,  
23      including nutrition, the options for the food system to adapt and mitigate, synergies and trade-offs  
24      among these options, and enabling conditions for their adoption. The chapter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

28

### 29      **5.1.1 Food security and insecurity, the food system, and climate change**

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





1  
2 **Figure 5.1 Interlinkages between the climate system, food system, ecosystem (land, water and oceans),**  
3 **and socio-economic system. These systems operate at multiple scales, both global and regional. Food**  
4 **security is an outcome of the food system leading to human well-being, which is also indirectly linked with**  
5 **climate and ecosystems through the socio-economic system. Response options for sustainable (S)**  
6 **practices, mainly in terms of climate change mitigation (M) and adaptation (A) are represented by grey**  
7 **arrows. Adaptation measures can help to reduce negative impacts of climate change on the food system**  
8 **and ecosystems. Mitigation measures can reduce greenhouse gas emissions coming from the food system**  
9 **and ecosystems.**

#### 10 5.1.1.1 Food security as an outcome of the food system

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

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

24 According to FAO (2001a), *food security* is a situation that exists when all people, at all times, have  
25 physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary  
26 needs and food preferences for an active and healthy life. “All people at all times” implies the need  
27 for equitable and stable food distribution, but it is increasingly recognised that it also covers the need  
28 for inter-generational equity, and therefore “sustainability” in food production. “Safe and nutritious  
29 food ...for a healthy life” implies that food insecurity can occur if the diet is not nutritious, including  
30 when there is consumption of an excess of calories, or if food is not safe, meaning free from harmful  
31 substances.

1 A prime impact of food insecurity is *malnourishment* (literally “bad nourishment”) leading to  
 2 *malnutrition*, which refers to deficiencies, excesses, or imbalances in a person’s intake of energy  
 3 and/or nutrients. As defined by FAO et al. (2018), undernourishment occurs when an individual’s  
 4 habitual food consumption is insufficient to provide the amount of dietary energy required to maintain  
 5 a normal, active, healthy life. In addition to undernourishment in the sense of insufficient calories  
 6 (“hunger”), undernourishment occurs in terms of nutritional deficiencies in vitamins (e.g., Vitamin A)  
 7 and minerals (e.g., iron, zinc, iodine), so-called “hidden hunger”. Hidden hunger tends to be present in  
 8 countries with high levels of undernourishment (Muthayya et al. 2013), but micronutrient deficiency  
 9 can occur in societies with low prevalence of undernourishment. For example, in many parts of the  
 10 world teenage girls suffer from iron deficiency (Whitfield et al. 2015) and calcium deficiency is  
 11 common in Western-style diets (Aslam and Varani 2016). Food security is related to nutrition, and  
 12 conversely food insecurity is related to malnutrition. Not all malnourishment arises from food  
 13 insecurity, as households may have access to healthy diets but choose to eat unhealthily, or it may  
 14 arise from illness. However, in many parts of the world, poverty is linked to poor diets (FAO et al.  
 15 2018). This may be through lack of resources to produce or access food in general, or healthy food, in  
 16 particular, as healthier diets are more expensive than diets rich in calories but poor in nutrition (*high*  
 17 *confidence*) (see meta-analysis by Darmon and Drewnowski 2015). The relationship between poverty  
 18 and poor diets may also be linked to unhealthy “food environments,” with retail outlets in a locality  
 19 only providing access to foods of low-nutritional quality (Gamba et al. 2015) – such areas are  
 20 sometimes termed “food deserts” (Battersby 2012).

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

28

### 29 **5.1.1.2 Effects of climate change on food security**

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

34 While most studies continue to focus on availability via impacts on food production, more studies are  
 35 addressing related issues of access (e.g., impacts on food prices), utilisation (e.g., impacts on  
 36 nutritional quality), and stability (e.g., impacts of increasing extreme events) as they are affected by a  
 37 changing climate (Bailey et al. 2015). Low-income producers and consumers are likely to be most  
 38 affected because of a lack of resources to invest in adaptation and diversification measures (UNCCD  
 39 2017; Bailey et al. 2015).

40

41 **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 <i>Production</i>	Reduced yields in crop and livestock systems	5.2.2.1, 5.2.2.2	Development of adaptation practices	5.3

<i>of food and its readiness for use through storage, processing, distribution, sale and/or exchange</i>	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 demand on 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
<i>Access: Ability to obtain food, including effects of price</i>	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
<i>Utilisation Achievement of food potential through nutrition, cooking, health</i>	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 <sub>2</sub>	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		
<i>Stability Continuous availability and access to food without disruption</i>	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 <i>Systemic impacts from interactions of all four pillars</i>	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 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

1

## 2 **5.1.2 Status of the food system, food insecurity, and malnourishment**

### 3 **5.1.2.1 Trends in the global food system**

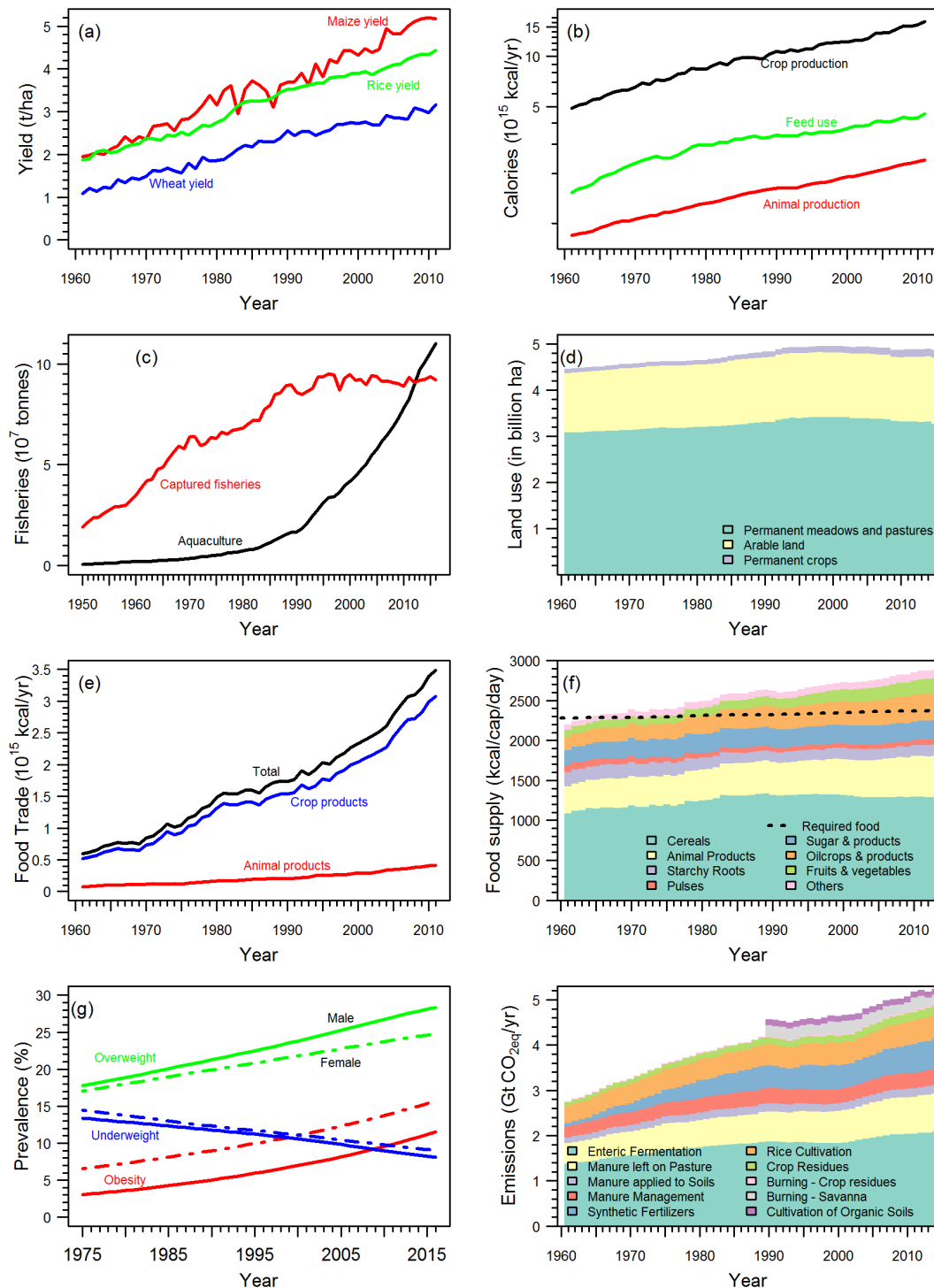
4 Food is predominantly produced on land, with, on average, 83% of the 697 kg of food consumed per  
 5 person per year, 93% of the 2884 kcal per day, and 80% of the 81 g of protein eaten per day coming  
 6 from terrestrial production in 2013 (FAOSTAT 2018)<sup>1</sup>. With increases in crop yields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

13 The availability of cereals, animal products, oil crops, and fruits and vegetables has mainly grown  
 14 (FAOSTAT 2018), reflecting shifts towards more affluent diets. This, in general, has resulted in a  
 15 decrease in prevalence of underweight and an increase in prevalence of overweight and obesity  
 16 among adults (Abarca-Gómez et al. 2017). During the period 1961-2016, anthropogenic greenhouse  
 17 gas emissions associated with agricultural production has grown from 3.1 Gt CO<sub>2</sub>-eq yr<sup>-1</sup> to 5.8 Gt  
 18 CO<sub>2</sub>-eq yr<sup>-1</sup> (Section 5.4.2, Chapter 2). The increase in emissions is mainly from the livestock sector  
 19 (from enteric fermentation and manure left on pasture), use of synthetic fertiliser, and rice cultivation  
 20 (FAOSTAT 2018).

21

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<sup>1</sup> FOOTNOTE: Does not take into account terrestrial production of feed.



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**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).

### 5.1.2.2 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 5.2g 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 5) 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 5 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 Asia and Pacific (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% 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).

**Table 5.2 Global prevalence of various forms of malnutrition**

	<b>HLPE 2017 (UN)</b>	<b>SOFI 2017 (FAO)</b>	<b>GNR 2017</b>	<b>SOFI 2018 (FAO)</b>	<b>GNR2018</b>
Overweight but not obese <sup>a</sup>	1.3 billion		1.93 billion		1.34 billion (38,9%) <sup>c</sup>
Overweight under five	41 million	41 million	41 million	38 million	38 million
Obesity <sup>b</sup>	600 million	600 million (13%)	641 million	672 million	678 million (13,1%) <sup>c</sup>
Undernourishment	800 million	815 million	815 million	821 million	
Stunting under five	155 million	155 million	155 million <sup>d</sup>	151 million	151 million <sup>d</sup> (22%)
Wasting under five	52 million	52 million (8%)	52 million <sup>d</sup>	50 million	51 million <sup>d</sup> (7%)
MND (iron)	19.2% of pregnant women <sup>e</sup>	33% women of reproductive age	613 million women and girls aged 15 to 49 <sup>f</sup>	613 million (32.8%) women and girls aged 15 to 49 <sup>f</sup>	613 million (32.8%) women and girls aged 15 to 49 <sup>f</sup>

*HLPE*: High Level Panel of Experts of the committee of world food security; *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 anemia as a proxy (percentage of pregnant women whose haemoglobin level is less than 110

1 grams per litre at sea level and percentage of non-pregnant women whose haemoglobin level is less than 120  
2 grams per litre at sea level).

3 <sup>a</sup>Body mass index between 25-29.9 kg/m<sup>2</sup>

4 <sup>b</sup>Body mass index greater than 30 kg/m<sup>2</sup>

5 <sup>c</sup>Prevalence of overweight/obesity among adults (age ≥18) in year 2016. Data from NCD Risk data source.

6 <sup>d</sup>UNICEF WHO Joint Malnutrition;

7 <sup>e</sup>In 2011

8 <sup>f</sup>Anaemia prevalence in girls and women aged 15 to 49

9

10 Globally, as the availability of inexpensive calories from commodity crops increases, so does per  
11 capita consumption of calorie-dense foods (Ng et al. 2014; NCD-RisC 2016a; Abarca-Gómez et al.  
12 2017; Doak and Popkin 2017). As a result, in every region of the world, the prevalence of obesity  
13 (body mass index >30 kg/m<sup>2</sup>) and overweight (body mass index range between normality [18.5-24.9]  
14 and obesity) is increasing. There are now more obese adults in the world than underweight adults (Ng  
15 et al. 2014; NCD-RisC 2016a; Abarca-Gómez et al. 2017; Doak and Popkin 2017). In 2016, around  
16 two billion adults were overweight, including 678 million suffering from obesity (NCD-RisC 2016a;  
17 Abarca-Gómez et al. 2017). The prevalence of overweight and obesity has been observed in all age  
18 groups.

19 Around 41 million children under five years and 340 million children and adolescents aged 5–19  
20 years were suffering from overweight or obesity in 2016 (NCD-RisC 2016a; FAO et al. 2017; WHO  
21 2015). In many high-income countries, the rising trends in children and adolescents suffering from  
22 overweight and obesity have stagnated at high levels; however, these have accelerated in parts of Asia  
23 and have very slightly reduced in European and Central Asian lower and middle-income countries  
24 (Abarca-Gómez et al. 2017; Doak and Popkin 2017; Christmann et al. 2009).

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

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

41 As discussed in Section 5.1.1.1, different methods of assessing food insecurity can provide differential  
42 pictures. Of particular note is the spatial distribution of food insecurity, especially in higher-income  
43 countries. FAO et al. (2018) reports FIES estimates of severe food insecurity in Africa, Asia and Latin  
44 America of 29.8%, 6.9% and 9.8% of the population, respectively, but of 1.4% of the population (i.e.,  
45 about 20 million in total; pro rata <5 million for US, <1 million for UK) in Europe and North  
46 America. However, in the United States, USDA estimates 40 million people were exposed to varying  
47 degrees of food insecurity, from mild to severe (overall prevalence about 12%) (Coleman-Jensen et al.  
48 2018). In the UK, estimates from 2017 and 2018 indicate about 4 million adults are moderately to

1 severely food insecure (prevalence 8%) (End Hunger UK 2018; Bates et al. 2017). The UK food bank  
2 charity, the Trussell Trust, over a year in 2017/18, distributed 1,332,952 three-day emergency food  
3 parcels to people referred to the charity as being in food crisis. Furthermore, a 2003 study in the UK  
4 (Schenker 2003) estimated that 40% of adults, and 15% of children, admitted to hospitals were  
5 malnourished, and that 70% of undernourishment in the UK was unreported.

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

### 12 **5.1.3 Climate change, gender, and equity**

13 Throughout, the chapter considers many dimensions of gender and equity in regard to climate change  
14 and the food system (Box 5.1). Climate change impacts differ among diverse social groups depending  
15 on factors such as age, ethnicity, ability/disability, sexual orientation, gender, wealth, and class (*high*  
16 *confidence*) (Vincent and Cull 2014; Kaijser and Kronsell 2014). Poverty, along with socio-economic  
17 and political marginalisation, cumulatively put women, children and the elderly in a disadvantaged  
18 position in coping with the adverse impacts of the changing climate (UNDP 2013; Skoufias et al.  
19 2011). The contextual vulnerability of women is higher due to their differentiated relative power,  
20 roles, and responsibilities at the household and community levels (Bryan and Behrman 2013; Nelson  
21 et al. 2002). They often have a higher reliance on subsistence agriculture, which will be severely  
22 impacted by climate change (Aipira et al. 2017).

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

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

37 Finally, climate change can affect human health in other ways that interact with food utilisation. In  
38 many parts of the world where agriculture relies still on manual labour, projections are that heat stress  
39 will reduce the hours people can work, and increase their risk (Dunne et al. 2013). For example,  
40 Takakura et al (2017) estimates that under RCP8.5, the global economic loss from people working  
41 shorter hours to mitigate heat loss may be 2.4–4% of GDP. Furthermore, as discussed by (Watts et al.  
42 2018); people's nutritional status interacts with other stressors and affects their susceptibility to ill  
43 health (the "utilisation pillar" of food security): so food-insecure people are more likely to be  
44 adversely affected by extreme heat, for example.

45 In the case of food price hikes, those more vulnerable are more affected (Uraguchi 2010), especially  
46 in urban areas (Ruel et al. 2010), where livelihood impacts are particularly severe for the individuals



1 and groups that have scarce resources or are socially isolated (Revi et al. 2014; Gasper et al. 2011)  
2 (*high confidence*). These people often lack power and access to resources, adequate urban services  
3 and functioning infrastructure. As climate events become more frequent and intense, this can increase  
4 the scale and depth of urban poverty (Rosenzweig et al. 2018b). Urban floods and droughts may result  
5 in water contamination increasing the incidence of diarrhoeal illness in poor children (Bartlett 2008).  
6 In the near destruction of New Orleans by Hurricane Katrina, about 40,000 jobs were lost (Rosemberg  
7 2010).

### 9 **Box 5.1 Gender, food security, and climate change**

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

#### 25 **Gender dimensions of the four pillars**

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

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

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

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

#### 42 **Integrating gender into adaptation**

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

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

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

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

19 Where gender-sensitive policies to climate change may exist, effective implementation in practice of  
20 gender equality and empowerment may not be achieved on the ground due to lack of technical  
21 capacity, financial resources and evaluation criteria, as shown in the Pacific Islands (Aipira et al.  
22 2017). Thus, corresponding institutional frameworks that are well-resourced, coordinated, and  
23 informed are required, along with adequate technical capacity within government agencies, NGOs and  
24 project teams, to strength collaboration and promote knowledge sharing (Aipira et al. 2017).

#### 25 **Women’s empowerment: Synergies among adaptation, mitigation, and food security**

26 Empowered and valued women in their societies increases their capacity to improve food security  
27 under climate change, make substantial contributions to their own well-being, to that of their families  
28 and of their communities (Langer et al. 2015; Ajani et al. 2013; Alston 2014) (*high confidence*).  
29 Women’s empowerment includes economic, social and institutional arrangements and may include  
30 targeting men in integrated agriculture programs to change gender norms and improve nutrition (Kerr  
31 et al. 2016). Empowerment through collective action and groups-based approaches in the near-term  
32 has the potential to equalise relationships on the local, national and global scale (Ringler et al. 2014).  
33 Empowered women are crucial to creating effective synergies among adaptation, mitigation, and food  
34 security.

35 In Western Kenya, widows in their new role as main livelihood providers invested in sustainable  
36 innovations like rainwater harvesting systems and agroforestry (this can serve as both adaptation and  
37 mitigation), and worked together in formalised groups of collective action (Gabrielsson and Ramasar  
38 2013) to ensure food and water security. In Nepal, women’s empowerment had beneficial outcomes in  
39 maternal and children nutrition, reducing the negative effect of low production diversity (Malapit et  
40 al. 2015). Integrated nutrition and agricultural programs have increased women’s decision-making  
41 power and control over home gardens in Burkina Faso (van den Bold et al. 2015) with positive  
42 impacts on food security.

#### 44 **5.1.4 Food systems in AR5, SR15, and the Paris Agreement**

45 Food, and its relationship to the environment and climate change, has grown in prominence since the  
46 Rio Declaration in 1992, where food production is Chapter 14 of Agenda 21, to the Paris Agreement

1 of 2015, which includes the need to ensure food security under the threat of climate change on its first  
2 page. This growing prominence of food is reflected in recent IPCC reports, including its Fifth  
3 Assessment Report (IPCC 2014a) and the Special Report on Global Warming of 1.5°C (SR15) (IPCC  
4 2018a).

5

#### 6 **5.1.4.1 Food systems in AR5 and SR15**

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

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

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

1 Many climate change response options in IPCC WG II and WG III AR5 (IPCC 2014b) address  
2 incremental adaptation or mitigation responses separately rather than being inclusive of more  
3 systemic or transformational changes in multiple food systems that are large-scale, in depth, and  
4 rapid, requiring social, technological, organisational and system responses (Rosenzweig and Solecki  
5 2018; Mapfumo et al. 2017; Termeer et al. 2017). In many cases, transformational change will require  
6 integration of resilience and mitigation across all parts of the food system including production,  
7 supply chains, social aspects, and dietary choices. Further, these transformational changes in the food  
8 system need to encompass linkages to ameliorative responses to land degradation (see Chapter 4),  
9 desertification (see Chapter 3), and declines in quality and quantity of water resources throughout the  
10 food-energy-water nexus (Chapter 2; Section 5.7).

11 The IPCC Special Report on Global Warming of 1.5°C found that climate-related risks to food  
12 security are projected to increase with global warming of 1.5°C and increase further with 2°C (IPCC  
13 2018a).

14

#### 15 **5.1.4.2 Food systems and the Paris Agreement**

16 To reach the temperature goal put forward in the Paris Agreement of limiting warming to well below  
17 2°C, and pursuing efforts to limit warming to 1.5°C, representatives from 196 countries signed the  
18 United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement (UNFCCC  
19 2015) in December 2015. The Agreement put forward a temperature target of limiting warming to  
20 well below 2°C, and pursuing efforts to limit warming to 1.5°C. Under the Paris Agreement, Parties  
21 are expected to put forward their best efforts through nationally determined contributions (NDCs) and  
22 to strengthen these efforts in the years ahead. Article 2 of the Agreement makes clear the agreement is  
23 within “the context of sustainable development” and states actions should be “in a manner that does  
24 not threaten food production” to ensure food security.

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

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

45 Most scenarios assume very rapid deployment between 2030 and 2050, reaching rates of expansion in  
46 land use in 1.5°C scenarios exceeding 20 M ha yr<sup>-1</sup>, which are unprecedented for crops and forestry  
47 reported in the FAO database from 1961. Achieving the 1.5 °C target would thus result in major

1 competing demands for land between climate change mitigation and food production, with cascading  
2 impacts on food security.

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

10

#### 11 **5.1.4.3 Charting the future of food security**

12 This chapter utilises the common framework of the Representative Concentration Pathways (RCPs)  
13 and the Shared Socio-economic Pathways (SSPs) (Popp et al. 2017; Riahi et al. 2017; Doelman et al.  
14 2018) to assess the impacts of future GHG emissions, mitigation measures, and adaptation on food  
15 security (See Cross-Chapter Box 1: Scenarios in Chapter 1, Section 5.2 and 5.6).

16 New work utilising these scenario approaches has shown that the food system externalises costs onto  
17 human health and the environment (Springmann et al. 2018a; Swinburn et al. 2019; Willett et al.  
18 2019), leading to calls for transforming the food system to deliver better human and sustainability  
19 outcomes (Willett et al. 2019; IAP 2018; Development Initiatives 2018; Lozano et al. 2018). Such a  
20 transformation could be an important lever to address the complex interactions between climate  
21 change and food security. Through acting on mitigation and adaptation in regard to both food demand  
22 and food supply we assess the potential for improvements to both human health and the Sustainable  
23 Development Goals (Section 5.6).

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

32 The chapter assesses new work on the observed and projected effects of CO<sub>2</sub> concentrations on the  
33 nutritional quality of crops (Section 5.2.4.2) and emphasises the role of extreme climate events  
34 (Section 5.2.5.1), social aspects including gender and equity (Box 5.1. and Cross-chapter Box 11:  
35 Gender in Chapter 7), and dietary choices (Section 5.4.6, 5.5.2). Other topics with considerable new  
36 literature include impacts on smallholder farming systems (Section 5.2.2.6), food loss and waste  
37 (Section **Error! Reference source not found.**), and urban and peri-urban agriculture (Section 5.6.5).  
38 he chapter explores the potential competing demands for land that mitigation measures to achieve  
39 temperature targets may engender, with cascading impacts on food production, food security, and  
40 farming systems (Section 5.6), and the enabling conditions for achieving the mitigation and adaptation  
41 in equitable and sustainable ways (Section 5.7). Section 5.8 presents challenges to future food  
42 security, including food price spikes, migration, and conflict.

43

## 1        **5.2 Impacts of climate change on food systems**

2        There are many routes by which climate change can impact food security and thus human health  
3        (Watts et al. 2018; Fanzo et al. 2017). One major route is via climate change affecting the amount of  
4        food, both from direct impacts on yields (Section 5.2.2.1) and indirect effects through climate  
5        change’s impacts on water availability and quality, pests and diseases (Section 5.2.2.3), and  
6        pollination services (Section 5.2.2.4). Another route is via changing CO<sub>2</sub> in the atmosphere, affecting  
7        biomass and nutritional quality (Section 5.2.4.2). Food safety risks during transport and storage can  
8        also be exacerbated by changing climate (Section 5.2.4.1).

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

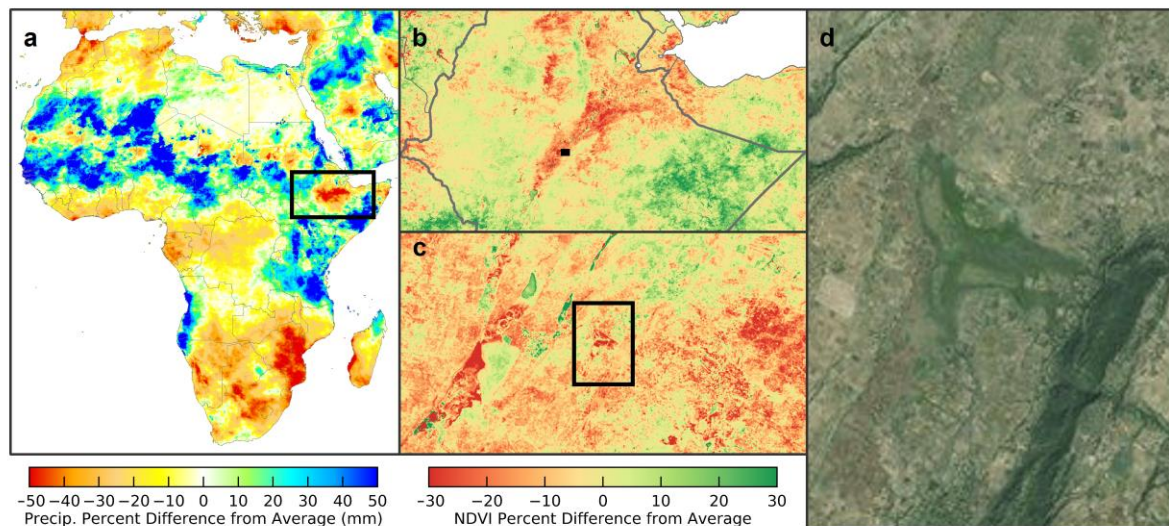
16        This section assesses recent literature on climate change impacts on the four pillars of food security:  
17        availability (Section 5.2.2), access (Section 5.2.3), utilisation (Section 5.2.4), and stability (Section  
18        5.2.5). It considers impacts on the food system from climate changes that are already taking place and  
19        how impacts are projected to occur in the future. See Supplementary Material Section SM5.2 for  
20        discussion of detection and attribution and improvement in projection methods.

21

### 22        **5.2.1 Climate drivers important to food security**

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

39



1  
2 **Figure 5.3** Precipitation anomaly and vegetation response in Eastern Africa. (a) Sep 2015–Feb 2016  
3 **Climate Hazards Group Infrared Precipitation with Station (CHIRPS) precipitation anomaly over Africa**  
4 **relative to the 1981–2010 average shows that large areas of Ethiopia received less than half of normal**  
5 **precipitation. Consequently, widespread impacts to agricultural productivity, especially within pastoral**  
6 **regions, were present across Ethiopia as evidenced by (d) reduced greenness in remote sensing images. (b)**  
7 **MODIS NDVI anomalies for Sep 2015–Feb 2016 relative to 2000–2015 average are shown for the inset**  
8 **box in (a). (c) Landsat NDVI anomalies for Sep 2015–Feb 2016 relative to 2000–2015 average are shown**  
9 **for the inset box in (b) (Huntington et al. 2017).**

10 Other variables that affect agricultural production, processing, and/or transport are solar radiation,  
11 wind, humidity, and (in coastal areas) salinisation and storm surge (Mutahara et al. 2016; Myers et al.  
12 2017). Extreme climate events resulting in inland and coastal flooding, can affect the ability of people  
13 to obtain and prepare food (Rao et al. 2016; FAO et al. 2018). For direct effects of atmospheric CO<sub>2</sub>  
14 concentrations on crop nutrient status see Section 5.2.4.2.

#### 15 16 **5.2.1.1 Short-lived climate pollutants**

17 The important role of short-lived climate pollutants such as ozone and black carbon is increasingly  
18 emphasised since they affect agricultural production through direct effects on crops and indirect  
19 effects on climate (Emberson et al. 2018; Lal et al. 2017; Burney and Ramanathan 2014; Ghude et al.  
20 2014) (see Chapters 2 and 4). Ozone causes damage to plants through damages to cellular metabolism  
21 that influence leaf-level physiology to whole-canopy and root-system processes and feedbacks; these  
22 impacts affect leaf-level photosynthesis senescence and carbon assimilation, as well as whole-canopy  
23 water and nutrient acquisition and ultimately crop growth and yield (Emberson et al. 2018). Using  
24 atmospheric chemistry and a global integrated assessment model, Chuwah et al. (2015) found that  
25 without a large decrease in air pollutant emissions, high ozone concentration could lead to an increase  
26 in crop damage of up to 20% in agricultural regions in 2050 compared to projections in which  
27 changes in ozone are not accounted for. Higher temperatures are associated with higher ozone  
28 concentrations; C3 crops are sensitive to ozone (e.g., soybeans, wheat, rice, oats, green beans,  
29 peppers, and some types of cottons) and C4 crops are moderately sensitive (Backlund et al. 2008).

30 Methane increases surface ozone which augments warming-induced losses and some quantitative  
31 analyses now include climate, long-lived (CO<sub>2</sub>) and multiple short-lived pollutants (CH<sub>4</sub>, O<sub>3</sub>)  
32 simultaneously (Shindell et al. 2017; Shindell 2016). Reduction of tropospheric ozone and black  
33 carbon can avoid premature deaths from outdoor air pollution and increases annual crop yields  
34 (Shindell et al. 2012). These actions plus methane reduction can influence climate on shorter time

1 scales than those of carbon dioxide–reduction measures. Implementing them substantially reduces the  
2 risks of crossing the 2°C threshold and contributes to achievement of the SDGs (Haines et al. 2017;  
3 Shindell et al. 2017).

## 5 5.2.2 Climate change impacts on food availability

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

### 9 5.2.2.1 Impacts on crop production

10 **Observed impacts.** Since AR5, there have been further studies that document impacts of climate  
11 change on crop production and related variables (See Supplementary Material Table SM5.3). There  
12 have been also a few studies that demonstrate a strengthening relationship between observed climate  
13 variables and crop yields that indicate future expected warming will have severe impacts on crop  
14 production (Mavromatis 2015; Innes et al. 2015). At the global scale, Iizumi et al. (2018) used a  
15 counterfactual analysis and found that climate change between 1981-2010 has decreased global mean  
16 yields of maize, wheat, and soybeans by 4.1, 1.8 and 4.5%, respectively, relative to preindustrial  
17 climate, even when CO<sub>2</sub> fertilisation and agronomic adjustments are considered. Uncertainties (90%  
18 probability interval) in the yield impacts are -8.5 to +.5% for maize, -7.5 to +4.3% for wheat, and -8.4  
19 to -0.5% for soybeans. For rice, no significant impacts were detected. This study suggests that climate  
20 change has modulated recent yields on the global scale and led to production losses, and that  
21 adaptations to date have not been sufficient to offset the negative impacts of climate change,  
22 particularly at lower latitudes.

23 Dryland settlements are perceived as vulnerable to climate change with regard to food security,  
24 particularly in developing countries; such areas are known to have low capacities to cope effectively  
25 with decreasing crop yields (Shah et al. 2008; Nellemann et al. 2009). This is of concern because  
26 drylands constitute over 40% of the earth’s land area, and are home to 2.5 billion people (FAO et al.  
27 2011).

28 *Australia.* In Australia, declines in rainfall and rising daily maximum temperatures based on  
29 simulations of 50 sites caused water-limited yield potential to decline by 27% from 1990 to 2015,  
30 even though elevated atmospheric CO<sub>2</sub> concentrations had a positive effect (Hochman et al. 2017). In  
31 New South Wales, high-temperature episodes during the reproduction stage of crop growth were  
32 found to have negative effects on wheat yields, with combinations of low rainfall and high  
33 temperatures being the most detrimental (Innes et al. 2015).

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

44 There have also been documented changes in winter wheat phenology in Northwest China (He 2015).  
45 Consistent with this finding, dates of sowing and emergence of spring and winter wheat were delayed,  
46 dates of anthesis and maturity was advanced, and length of reproductive growth period was prolonged



1 from 1981-2011 in a study looking at these crops across China (Liu et al. 2018b). Another study  
2 looking in Norwest China demonstrated that there have been changes in the phenology and  
3 productivity of spring cotton (Huang and Ji 2015). A study looking at wheat growth and yield in  
4 different climate zones of China from 1981-2009 found that impacts were positive in Northern China  
5 and negative in Southern China (Tao et al. 2014). Temperature increased across the zones while  
6 precipitation changes were not consistent (Tao et al. 2014).

7 Crop yield studies focusing on India have found that warming has reduced wheat yields by 5.2% from  
8 1981 to 2009, despite adaptation (Gupta et al. 2017); that maximum daytime temperatures have risen  
9 along with some night-time temperatures (Jha and Tripathi 2017).

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

15 Mountain people in the Hindu-Kush Himalayan region encompassing parts of Pakistan, India, Nepal,  
16 and China, are particularly vulnerable to food insecurity related to climate change because of poor  
17 infrastructure, limited access to global markets, physical isolation, low productivity, and hazard  
18 exposure, including Glacial Lake Outburst Floods (GLOFs) (Rasul et al. 2019; Rasul 2010; Tiwari  
19 and Joshi 2012; Huddleston et al. 2003; Ward et al. 2013; FAO 2008; Nautiyal et al. 2007; Din et al.  
20 2014). Surveys have been conducted to determine how climate-related changes have affected food  
21 security (Hussain et al. 2016; Shrestha and Nepal 2016) with results showing that the region is  
22 experiencing an increase in extremes, with farmers facing more frequent floods as well as prolonged  
23 droughts with ensuing negative impacts on agricultural yields and increases in food insecurity  
24 (Hussain et al. 2016; Manzoor et al. 2013).

25 *South America.* In another mountainous region, the Andes, inhabitants are also beginning to  
26 experience changes in the timing, severity, and patterns of the annual weather cycle. Data collected  
27 through participatory workshops, semi-structured interviews with agronomists, and qualitative  
28 fieldwork from 2012 to 2014 suggest that in Colomi, Bolivia climate change is affecting crop yields  
29 and causing farmers to alter the timing of planting, their soil management strategies, and the use and  
30 spatial distribution of crop varieties (Saxena et al. 2016). In Argentina, there has also been an increase  
31 in yield variability of maize and soybeans (Iizumi and Ramankutty 2016). These changes have had  
32 important implications for the agriculture, human health, and biodiversity of the region (Saxena et al.  
33 2016).

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

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

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

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

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

26 **Projected impacts.** Climate change effects have been studied on a global scale following a variety of  
27 methodologies that have recently been compared (Lobell and Asseng 2017; Zhao et al. 2017a; Liu et  
28 al. 2016). Approaches to study global and local changes include global gridded crop model  
29 simulations (e.g., (Deryng et al. 2014)), point-based crop model simulations (e.g., (Asseng et al.  
30 2015)), analysis of point-based observations in the field (e.g., (Zhao et al. 2016)), and temperature-  
31 yield regression models (e.g., (Auffhammer and Schlenker 2014)). For an evaluation of model skills  
32 see e.g., used in AgMIP see Müller et al. (2017b).

33 Results from Zhao et al. (2017a) across different methods consistently showed negative temperature  
34 impacts on crop yield at the global scale, generally underpinned by similar impacts at country and site  
35 scales. A limitation of Zhao et al. (2017a) is that it is based on the assumption that yield responses to  
36 temperature increase are linear, while yield response differs depending on growing season  
37 temperature level. Iizumi et al. (2017) showed that the projected global mean yields of maize and  
38 soybean at the end of this century do decrease monotonically with warming, whereas those of rice and  
39 wheat increase with warming and level off at a warming of about 3°C (2091–2100 relative to 1850–  
40 1900).

41 Empirical statistical models have been applied widely to different cropping systems, at multiple  
42 scales. Analyses using statistical models for maize and wheat tested with global climate model  
43 scenarios found that the RCP4.5 scenario reduced the size of average yield impacts, risk of major  
44 slowdowns, and exposure to critical heat extremes compared to RCP8.5 in the latter decades of the  
45 21st century (Tebaldi and Lobell 2018). Impacts on crops grown in the tropics are projected to be  
46 more negative than in mid- to high-latitudes as stated in AR5 and confirmed by recent studies (e.g.,  
47 (Levis et al. 2018)). These projected negative effects in the tropics are especially pronounced under  
48 conditions of explicit nitrogen stress (Figure 5.4) (Rosenzweig et al. 2014).

## GGCMs with explicit N stress



**Figure 5.4 Median yield changes (%) for RCP8.5 (2070–2099 in comparison to 1980–2010 baseline) with CO<sub>2</sub> 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). Gray areas indicate historical areas with little to no yield capacity. All models use a 0.5° 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).**

Reyer et al. (2017b) examined biophysical impacts in five world regions under different warming scenarios - 1, 1.5, 2, and 4 °C warming. For the Middle East and Northern Africa region a significant correlation between crop yield decrease and temperature increase was found, regardless of whether the effects of CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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, there are mixed results of positive and negative changes 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).

1 However, the study found the projected total land area in 2050, including regions not currently used  
2 for crops, climatically suitable for a high attainable yield similar to today. This indicates that large  
3 shifts in land-use patterns and crop choice will likely be necessary to sustain production growth and  
4 keep pace with current trajectories of demand.

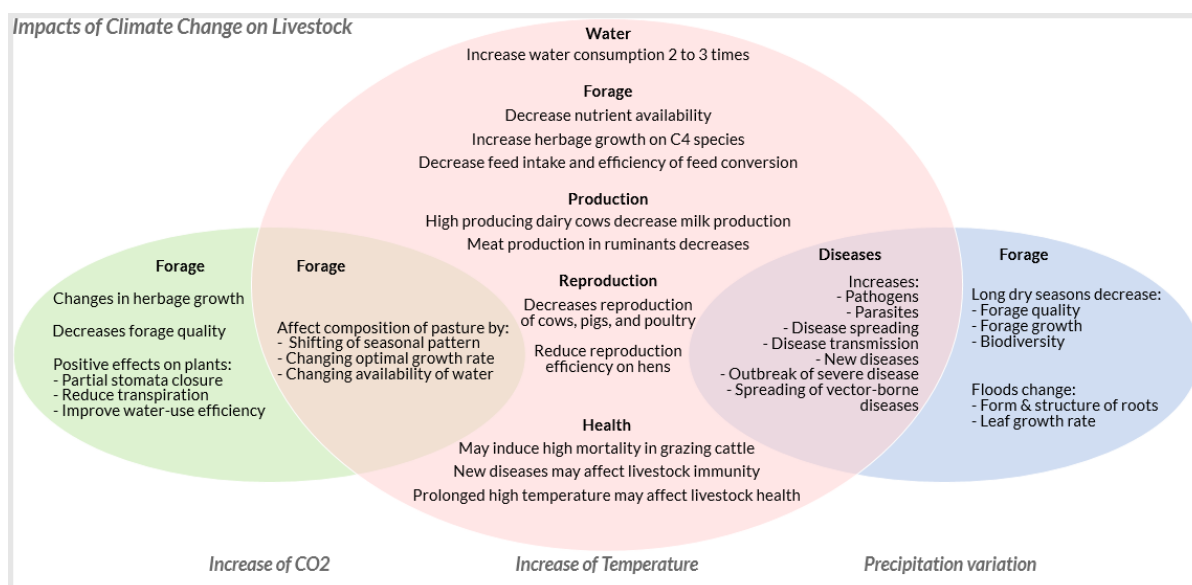
5 *Fruits and vegetables.* Understanding the full range of climate impacts on fruits and vegetables is  
6 important for projecting future food security, especially related to dietary diversity and healthy diets.  
7 However, studies for vegetables are very limited (Bisbis et al. 2018). Of the 174 studies considered in  
8 a recent review only 14 described results of field or greenhouse experiments studying impacts of  
9 increased temperatures on yields of different root and leafy vegetables, tomatoes and legumes  
10 (Scheelbeek et al. 2018). Bisbis et al. (2018) found similar effects for vegetables as have been found  
11 for grain crops, that is, the effect of increased CO<sub>2</sub> on vegetables is mostly beneficial for production,  
12 but may alter internal product quality, or result in photosynthetic down-regulation. Heat stress reduces  
13 fruit set of fruiting vegetables, and speeds up development of annual vegetables, shortening their time  
14 for photoassimilation. Yield losses and impaired product quality result, thereby increasing food loss  
15 and waste. On the other hand, a longer growing season due to warmer temperatures enables a greater  
16 number of plantings and can contribute to greater annual yields. However, some vegetables, such as  
17 cauliflower and asparagus, need a period of cold accumulation to produce a harvest and warmer  
18 winters may not provide those requirements.

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

26 In summary, studies assessed find that climate change will increasingly be detrimental to crop  
27 productivity as levels of warming progress (*high confidence*). Impacts will vary depending on CO<sub>2</sub>  
28 concentrations, fertility levels, and region. Productivity of major commodity crops as well as crops  
29 such as millet and sorghum yields will be affected. Studies on fruits and vegetables find similar  
30 effects to those projected for grain crops in regard to temperature and CO<sub>2</sub> effects. Total land area  
31 climatically suitable for high attainable yield, including regions not currently used for crops, will be  
32 similar in 2050 to today.

### 34 **5.2.2.2 Impacts on livestock production systems**

35 Livestock systems are impacted by climate change mainly through increasing temperatures and  
36 precipitation variation, as well as atmospheric carbon dioxide (CO<sub>2</sub>) concentration and a combination  
37 of these factors. Temperature affects most of the critical factors of livestock production, such as water  
38 availability, animal production and reproduction, and animal health (mostly through heat stress)  
39 (Figure 5.5). Livestock diseases are mostly affected by increases in temperature and precipitation  
40 variation (Rojas-Downing et al. 2017). Impacts of climate change on livestock productivity,  
41 particularly of mixed and extensive systems, are strongly linked to impacts on rangelands and  
42 pastures, which include the effects of increasing CO<sub>2</sub> on their biomass and nutritional quality. This is  
43 critical considering the very large areas concerned and the number of vulnerable people affected  
44 (Steinfeld 2010; Morton 2007). Pasture quality and quantity are mainly affected through increases in  
45 temperature and CO<sub>2</sub>, 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, semiarid and arid pasture will likely have reduced livestock productivity, while nutritional quality will be affected by CO<sub>2</sub> 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 agro-pastoralists (McGahey et al. 2014). Observed impacts in pastoral systems reported in the literature include decreasing rangelands, decreasing mobility, decreasing livestock number, poor animal health, overgrazing, land degradation, decreasing productivity, decreasing access to water and feed, and increasing conflicts for the access to pasture land (López-i-Gelats et al. 2016; Batima et al. 2008; Njiru 2012; Fjelde and von Uexkull 2012; Raleigh and Kniveton 2012; Egeru 2016) (*high confidence*).

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

1 parts of China and tropical Asia (IPCC 2012). In Mongolia, grassland productivity has declined by  
2 20-30% over the latter half of the 20<sup>th</sup> century, and ewe average weight reduced by 4 kg on an annual  
3 basis, or about 8% since 1980 (Batima et al. 2008). Substantial decline in cattle herd sizes can be due  
4 to increased mortality and forced off-take (Megersa et al. 2014). Important but less studied is the  
5 impact of the interaction of grazing patterns with climate change on grassland composition. (Spence et  
6 al. 2014) showed that climate change effects on Mongolia mountain steppe could be contingent on  
7 land use.

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

12 Non-climate drivers add vulnerability of pastoral systems to climate change (McKune and Silva  
13 2013). For instance, during environmental disasters, livestock holders have been shown to be more  
14 vulnerable to food insecurity than their crop-producing counterparts because of limited economic  
15 access to food and unfavorable market exchange rates (Nori et al. 2005). Sami reindeers in Finland  
16 showed reduced freedom of action in response to climate change due to loss of habitat, increased  
17 predation, and presence of economic and legal constraints) (Tyler et al. 2007; Pape and Löffler 2012).  
18 In Tibet, emergency aid has provided shelters and privatised communally owned rangeland, which  
19 have increased the vulnerability of pastoralists to climate change (Yeh et al. 2014; Næss 2013).

20 **Projected impacts.** The impacts of climate change on global rangelands and livestock have received  
21 comparatively less attention than the impacts on crop production. Projected impacts on grazing  
22 systems include changes in herbage growth (due to changes in atmospheric CO<sub>2</sub> concentrations and  
23 rainfall and temperature regimes) and changes in the composition of pastures and in herbage quality,  
24 as well as direct impacts on livestock (Herrero et al. 2016b). Droughts and high temperatures in  
25 grasslands can also be a predisposing factor for fire occurrence (IPCC 2012).

26 *Net primary productivity, soil organic carbon, and length of growing period.* There are large  
27 uncertainties related to grasslands and grazing lands (Erb et al. 2016), especially in regard to net  
28 primary productivity (NPP) (Fetzel et al. 2017; Chen et al. 2018). Boone et al. (2017) estimated that  
29 the mean global annual net primary production (NPP) in rangelands may decline by 10 g C m<sup>-2</sup> yr<sup>-1</sup> in  
30 2050 under RCP 8.5, but herbaceous NPP is likely to increase slightly (i.e., average of 3 g C m<sup>-2</sup> yr<sup>-1</sup>)  
31 (Figure 5.6). Results of a similar magnitude were obtained by Havlík et al. (2015), using EPIC and  
32 LPJmL on a global basis (Rojas-Downing et al. 2017). According to Rojas-Downing et al. (2017), an  
33 increase of 2°C is estimate to negatively impact pasture and livestock production in arid and semiarid  
34 regions and positively impact humid temperate regions.

35 Boone et al. (2017) identified significant regional heterogeneity in responses, with large increases in  
36 annual productivity projected in northern regions (e.g., a 21% increase in productivity in the US and  
37 Canada) and large declines in western Africa (-46% in sub-Saharan western Africa) and Australia (-  
38 17%). Regarding the length of growing period (LGP, average number of growing days per year)  
39 (Herrero et al. 2016b) projected reductions in the lower latitudes due to changes in rainfall patterns  
40 and increases in temperatures, which indicate increasing limitations of water. They identified 35°C as  
41 a critical threshold for rangeland vegetation and heat tolerance in some livestock species.



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**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<sub>2</sub> fertilisation. Results from RCP 4.5 and 8.5, with and without positive effects of atmospheric CO<sub>2</sub> 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 colors are based on the spatial mean value plus or minus two standard deviations (Boone et al. 2017).**

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*Rangeland composition.* According to Boone et al. (2017), the composition of rangelands is projected to change as well (see 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 savannahs south of the Sahara, both shrub and tree cover are projected to increase, albeit at lower productivity and standing biomass. Rangelands in western and southwestern parts of the Isfahan province in Iran were found to be more vulnerable to future drying-warming conditions (Saki et al. 2018; Jaberlansar et al. 2017).

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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 savannahs south of the Sahara (see Chapter 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.

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*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



1 between 10°C–30°C, and at temperatures above this animals reduce their feed intake 3–5% per  
2 additional degree of temperature (NRC 1981). In addition to reducing animal production, higher  
3 temperatures negatively affect fertility (HLPE 2012).

4 Indirect impacts to mixed and extensive systems are mostly related to the impacts on the feed base,  
5 whether pastures or crops, leading to increased variability and sometimes reductions in availability  
6 and quality of the feed for the animals (Rivera-Ferre et al. 2016b). Reduced forage quality can  
7 increase CH<sub>4</sub> emissions per unit of gross energy consumed. Increased risk of animal diseases is also  
8 an important impact to all production systems (Bett et al. 2017). These depend on the geographical  
9 region, land use type, disease characteristics, and animal susceptibility (Thornton et al. 2009). Also  
10 important is the interaction of grazing intensity with climate change. Pfeiffer et al. (2019) estimated  
11 that in a scenario of mean annual precipitation below 500 mm increasing grazing intensity reduced  
12 rangeland productivity and increased annual grass abundance.

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

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

### 33 **5.2.2.3 Impacts on pests and diseases**

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

40 These mechanisms include changes in host susceptibility due to CO<sub>2</sub> concentration effects on crop  
41 composition and climate stresses; changes in the biology of pests and diseases or their vectors (e.g.,  
42 more generational cycles, changes in selection pressure driving evolution); mismatches in timing  
43 between pests or vectors and their ‘natural enemies’; changes in survival or persistence of pests or  
44 disease pathogens (e.g., changes in crop architecture driven by CO<sub>2</sub> fertilisation and increased  
45 temperature, providing a more favourable environment for persistence of pathogens like fungi), and  
46 changes in pest distributions as their “climate envelopes” shift. Such processes may affect pathogens,  
47 and their vectors, as well as plant, invertebrate and vertebrate pests. (Latham et al. 2015) .



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

6 There is *robust evidence* that pests and diseases have already responded to climate change (Bebber et  
7 al. 2014), and many studies have now built predictive models based on current incidence of pests,  
8 diseases or vectors that indicate how they may respond in future (e.g., (Caminade et al. 2015; Kim et  
9 al. 2015; Kim and Cho 2016; Samy and Peterson 2016; Yan et al. 2017)). Warren et al. (2018)  
10 estimate that about 50% of insects, which are often pests or disease vectors, will change ranges by  
11 about 50% by 2100 under current GHG emissions trajectories. These changes will lead to crop losses  
12 due to changes in insect pests (Deutsch et al. 2018) and weed pressure (Ziska et al. 2018), and thus  
13 affect pest and disease management at the farm level (Waryszak et al. 2018). For example, Samy and  
14 Peterson (2016) modelled Blue-tongue virus (BTV), which is spread by biting *Culicoides* midges,  
15 finding that the distribution of BTV is likely to be extended, particularly in central Africa, the US, and  
16 western Russia.

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

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

#### 32 33 **5.2.2.4 Impacts on pollinators**

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

45 Pollination services arise from a mutualistic interaction between an animal and a plant – which can be  
46 disrupted by climate's impacts on one or the other or both (Memmott et al. 2007). Disruption can  
47 occur through changes in species' ranges or by changes in timing of growth stages (Settele et al.

1 2016). For example, if plant development responds to different cues (e.g., day length) from insects  
2 (e.g., temperature), the emergence of insects may not match the flowering times of the plants, causing  
3 a reduction in pollination. Climate change will affect pollinator ranges depending on species, life-  
4 history, dispersal ability and location. Warren et al. (2018) estimate that under a 3.2°C warming  
5 scenario, the existing range of about 49% of insects will be reduced by half by 2100, suggesting either  
6 significant range changes (if dispersal occurs) or extinctions (if it does not). However, in principle,  
7 ecosystem changes caused by invasions, in some cases, could compensate for the decoupling  
8 generated between native pollinators and pollinated species (Schweiger et al. 2010).

9 Other impacts include changes in distribution and virulence of pathogens affecting pollinators, such as  
10 the fungus *Nosema ceranae*, which can develop at a higher temperature range than the less-virulent  
11 *Nosema apis*; increased mortality of pollinators due to higher frequency of extreme weather events;  
12 food shortage for pollinators due to reduction of flowering length and intensity; and aggravation of  
13 other threats, such as habitat loss and fragmentation (González-Varo et al. 2013; Goulson et al. 2015;  
14 Le Conte and Navajas 2008; Menzel et al. 2006; Walther et al. 2009; IPBES, 2016). The increase in  
15 atmospheric CO<sub>2</sub> is also reducing the protein content of pollen, with potential impact on pollination  
16 population biology (Ziska et al. 2016).

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

21

#### 22 **5.2.2.5 Impacts on aquaculture**

23 This report focuses on land-based aquaculture; for assessment of impacts on marine fisheries both  
24 natural and farmed see the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate  
25 (SROCC, forthcoming).

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

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

44 In many countries the projected declines co-occur across both marine fisheries and agricultural crops  
45 (Blanchard et al. 2017), both of which will impact the aquaculture and livestock sectors (See  
46 Supplementary Material Figure SM5.1). Countries with low Human Development Index, trade  
47 opportunities and aquaculture technologies are likely to face greater challenges. These cross-sectoral

1 impacts point to the need for a more holistic account of the inter-connected vulnerabilities of food  
2 systems to climate and global change.

3

#### 4 **5.2.2.6 Impacts on smallholder farming systems**

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

15 Smallholder farming systems have been recognised as highly vulnerable to climate change (Morton,  
16 2007) because they are highly dependent on agriculture and livestock for their livelihood (Dasgupta et  
17 al. 2014) (*high confidence*). In Zimbabwe, farmers were found vulnerable due to their marginal  
18 location, low levels of technology, and lack of other essential farming resources. Farmers observed  
19 high frequency and severity of drought, excessive precipitation, drying up of rivers, dams and wells,  
20 and changes in timing and pattern of seasons as evidence of climate change, and indicated that  
21 prolonged wet, hot, and dry weather conditions resulted in crop damage, death of livestock, soil  
22 erosion, bush fires, poor plant germination, pests, lower incomes, and deterioration of infrastructure  
23 (Mutekwa 2009).

24 In Madagascar, Harvey et al. (2014b) conducted surveyed 600 small farmers and found that chronic  
25 food insecurity, physical isolation and lack of access to formal safety nets increased Malagasy  
26 farmers' vulnerability to any shocks to their agricultural system, particularly extreme events. In  
27 Chitwan, Nepal, occurrence of extreme events and increased variability in temperature has increased  
28 the vulnerability of crops to biotic and abiotic stresses and altered the timing of agricultural  
29 operations; thereby affecting crop production (Paudel et al. 2014). In Lesotho, a study on subsistence  
30 farming found that food crops were the most vulnerable to weather, followed by soil and livestock.  
31 Climate variables of major concern were hail, drought and dry spells which reduced crop yields. In  
32 the Peruvian Altiplan, Sietz et al. (2012) evaluate smallholders' vulnerability to weather extremes  
33 with regard to food security and found the relevance of resource scarcity (livestock, land area),  
34 diversification of activities (lack of alternative income, education deprivation) and income restrictions  
35 (harvest failure risk) in shaping vulnerability of smallholders. See Section 5.2.2.6 for observed  
36 impacts on smallholder pastoral systems.

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

44 Farming system methods developed by AgMIP have been used in regional integrated assessments in  
45 Sub-Saharan Africa (Kihara et al. 2015), West Africa (Adiku et al. 2015); East Africa (Rao et al.  
46 2015), South Africa (Beletse et al. 2015), Zimbabwe (Masikati et al. 2015), South Asia (McDermid et  
47 al. 2015), Pakistan (Ahmad et al. 2015), the Indo-Gangetic Basin (Subash et al. 2015), Tamil Nadu

1 (Ponnusamy et al. 2015) and Sri Lanka (Zubair et al. 2015). The assessments found that climate  
2 change adds pressure to smallholder farmers across Sub-Saharan Africa and South Asia, with winners  
3 and losers within each area studied. Temperatures are expected to increase in all locations, and rainfall  
4 decreases are projected for the western portion of West Africa and Southern Africa, while increases in  
5 rainfall are projected for eastern West Africa and all study regions of South Asia. The studies project  
6 that climate change will lead to yield decreases in most study regions except South India and areas in  
7 central Kenya, as detrimental temperature effects overcome the positive effects of CO<sub>2</sub>. These studies  
8 use AgMIP representative agricultural pathways (RAPs) as a way to involve stakeholders in regional  
9 planning and climate resilience (Valdivia et al. 2015). RAPs are consistent with and complement the  
10 RCP/SSP approaches for use in agricultural model intercomparisons, improvement, and impact  
11 assessments

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

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

25 Climate change impacts on food, feed and cash crops other than cereals, often grown in smallholder  
26 systems or family farms are less often studied, although impacts can be substantial. For example,  
27 areas suitable for growing coffee are expected to decrease by 21% in Ethiopia with global warming of  
28 2.4°C (Moat et al. 2017) and more than 90% in Nicaragua (Läderach et al. 2017) with 2.2°C local  
29 temperature increase.

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

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

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

45

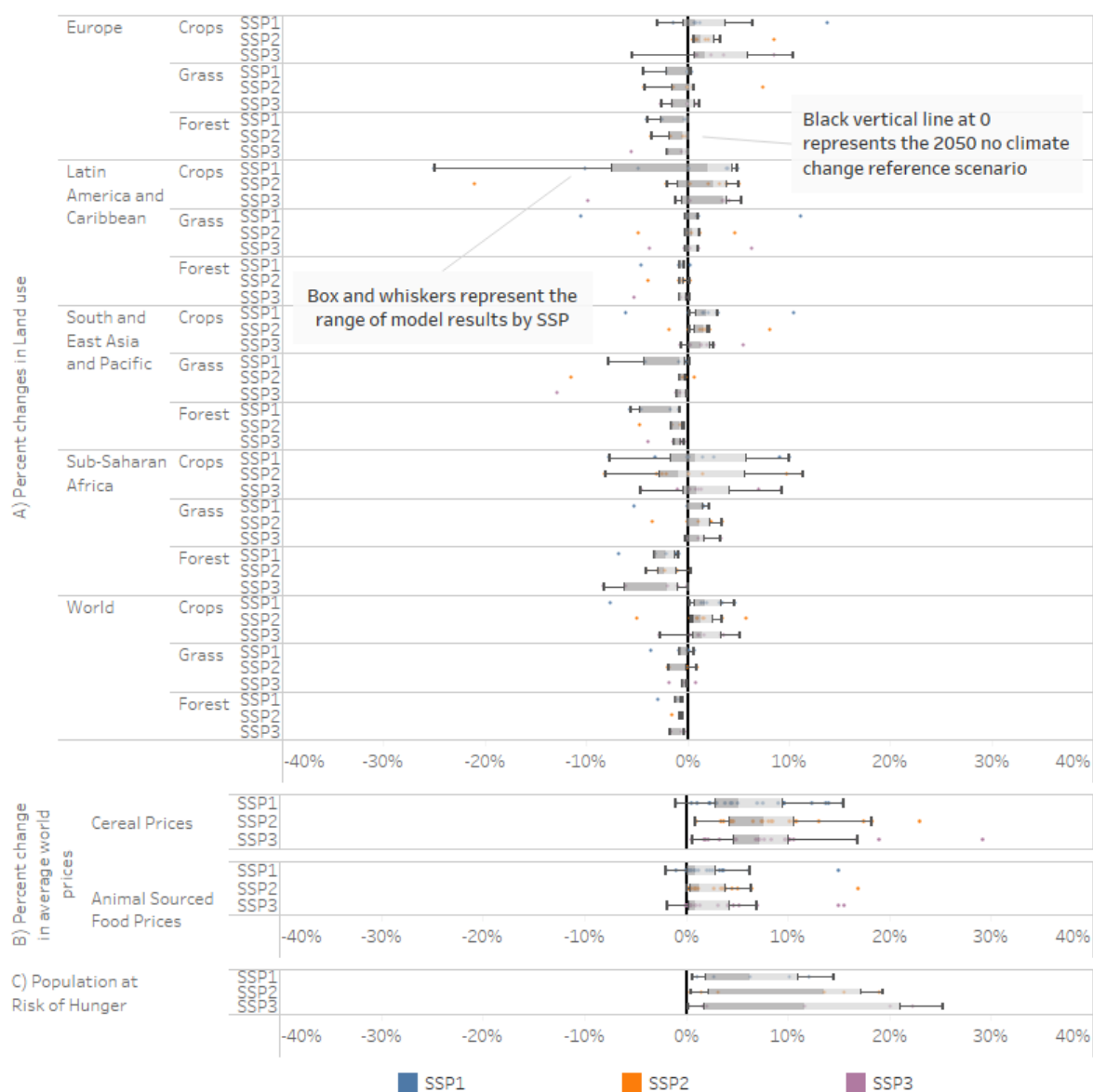
### 1 **5.2.3 Climate change impacts on access**

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

4

#### 5 **5.2.3.1 Impacts on prices and risk of hunger**

6 A protocol-based analysis based on AgMIP methods tested a combination of RCPs and SSPs to  
7 provide a range of projections for prices, risk of hunger, and land use change (Figure 5.7 and  
8 Supplementary Material Table SM5.4.) (Hasegawa et al. 2018). Previous studies have found that  
9 decreased agricultural productivity will depress agricultural supply, leading to price increases. Despite  
10 different economic models with various representations of the global food system (Valin et al. 2014;  
11 Robinson et al. 2014; Nelson et al. 2013; Schmitz et al. 2014), as well as having represented the SSPs  
12 in different ways (i.e., technological change, land-use policies, sustainable diets, etc. (Stehfest et al.  
13 2019; Hasegawa et al. 2018)), the ensemble of participating models projected a 1-29% cereal price  
14 increase in 2050 across SSPs 1, 2, and 3 due to climate change (RCP 6.0), which would impact  
15 consumers globally through higher food prices; regional effects will vary. The median cereal price  
16 increase was 7%, given current projections of demand. In all cases (across SSPs and global economic  
17 models), prices are projected to increase for rice and coarse grains, with only one instance of a price  
18 decline (-1%) observed for wheat in SSP1, with price increases projected in all other cases. Animal-  
19 sourced foods (ASFs) are also projected to see price increases (1%), but the range of projected price  
20 changes are about half those of cereals, highlighting that the climate impacts on ASFs is indirect  
21 through the cost and availability of feed, and that there is significant scope for feed substitution within  
22 the livestock sector.



1  
2 **Figure 5.7. Implications of climate change by 2050 on land-use, selected agricultural commodity prices,**  
3 **and the population at risk of hunger based on AgMIP Global Economic Model analysis. (A) Projected %**  
4 **change in land-use by 2050 by land type (cropland, grassland, and forest) and SSP. (B) Projected %**  
5 **changes in average world prices by 2050 for cereals (rice, wheat, and coarse grains) and animal sourced**  
6 **foods (ruminant meat, monogastric, and dairy) by SSP. (C) Percentage change by 2050 in the global**  
7 **population at risk of hunger by SSP.**

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

17 The extent that reduced energy intake leads to a heightened risk of hunger varies by global economic  
18 model. However, all models project an increase in the risk of hunger, with the median projection of an

1 increase in the population at risk of insufficient energy intake by 6, 14, and 12 % in 2050 for SSPs 1,  
2 2 and 3 respectively compared to a no climate change reference scenario. This median percentage  
3 increase would be the equivalent of 8, 24, and 80 million (full range 1-183 million) additional people  
4 at risk of hunger due to climate change (Hasegawa et al. 2018).

### 6 **5.2.3.2 Impacts on land use**

7 Climate change is likely to lead to changes in land use globally (Nelson et al. 2014; Schmitz et al.  
8 2014; Wiebe et al. 2015). Hasegawa et al. (2018) found that declining agricultural productivity  
9 broadly leads to the need for additional cropland, with 7 of 8 models projecting increasing cropland  
10 and the median increase by 2050 projected across all models of 2 % compared to a no climate change  
11 reference (Figure 5.7). Not all regions will respond to climate impacts equally, with more uncertainty  
12 on regional land-use change across the model ensemble than the global totals might suggest. For  
13 example, the median land-use change for Latin America is an increase of cropland by 3 %, but the  
14 range across the model ensemble is significant, with 3 models projecting declines in cropland (-25 –-1  
15 %) compared to the 5 models projecting cropland increase (0 – 5 %). For further discussion on land  
16 use change and food security see Section 5.6.

## 18 **5.2.4 Climate change impacts on food utilisation**

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

### 22 **5.2.4.1 Impacts on food safety and human health**

23 Climate change can influence food safety through changing the population dynamics of contaminating  
24 organisms due to, for example, changes in temperature and precipitation patterns, and also humidity,  
25 increased frequency and intensity of extreme weather events, and changes in contaminant transport  
26 pathways. Changes in food and farming systems, e.g., intensification to maintain supply under climate  
27 change, may also increase vulnerabilities as the climate changes (Tirado et al. 2010). Climate-related  
28 changes in the biology of contaminating organisms include changing the activity of mycotoxin-  
29 producing fungi, changing the activity of micro-organisms in aquatic food chains that cause disease  
30 (e.g., dinoflagellates, bacteria like *Vibrio*), and increasingly heavy rainfall and floods causing  
31 contamination of pastures with enteric microbes (like *Salmonella*) that can enter the human food  
32 chain. Degradation and spoilage of products in storage and transport can also be affected by changing  
33 humidity and temperature outside of cold chains, notably from microbial decay but also from potential  
34 changes in the population dynamics of stored product pests (e.g., mites, beetles, moths) (Moses et al.  
35 2015).

36 Mycotoxin-producing fungi occur in specific conditions of temperature and humidity, so climate  
37 change will affect their range, increasing risks in some areas (such as mid-temperate latitudes) and  
38 reducing them in others (e.g., the tropics) (Paterson and Lima 2010). There is *robust evidence* from  
39 process-based models of particular species (*Aspergillus*/Aflatoxin B1, *Fusarium*/deoxynivalenol) with  
40 projections of future climate that show that aflatoxin contamination of maize in southern Europe will  
41 increase significantly (Battilani et al. 2016), and deoxynivalenol contamination of wheat in north-west  
42 Europe will increase by up to 3 times (van der Fels-Klerx et al. 2012b,a). Whilst the downscaled  
43 climate models make any specific projection for a given geography uncertain (Van der Fels-Klerx et  
44 al. 2013), experimental evidence on the small scale suggests that the combination of rising CO<sub>2</sub> levels,  
45 affecting physiological processes in photosynthetic organisms, and temperature changes, can be  
46 significantly greater than temperature alone (Medina et al. 2014). Risks related to aflatoxins are likely

1 to change, but detailed projections are difficult because they depend on local conditions (Vaughan et  
2 al. 2016).

3 Foodborne pathogens in the terrestrial environment typically come from enteric contamination (from  
4 humans or animals), and can be spread by wind (blowing contaminated soil) or flooding – the  
5 incidence of both of which are likely to increase with climate change (Hellberg and Chu 2016).  
6 Furthermore, water stored for irrigation, which may be increased in some regions as an adaptation  
7 strategy, can become an important route for the spread of pathogens (as well as other pollutants);  
8 contaminated water and diarrheal diseases are acute threats to food security (Bond et al. 2018). Whilst  
9 there is little direct evidence (in terms of modelled projections) the results of a range of reviews, as  
10 well as expert groups, suggest that risks from foodborne pathogens are likely to increase through  
11 multiple mechanisms (Tirado et al. 2010; van der Spiegel et al. 2012; Liu et al. 2013; Kirezieva et al.  
12 2015; Hellberg and Chu 2016).

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

17 All of these factors will lead to regional differences regarding food safety impacts (Paterson and Lima  
18 2011). For instance, in Europe it is expected that most important food safety-related impacts will be  
19 mycotoxins formed on plant products in the field or during storage; residues of pesticides in plant  
20 products affected by changes in pest pressure; trace elements and/or heavy metals in plant products  
21 depending on changes in abundance and availability in soils; polycyclic aromatic hydrocarbons in  
22 foods following changes in long-range atmospheric transport and deposition; and presence of  
23 pathogenic bacteria in foods following more frequent extreme weather, such as flooding and heat  
24 waves (Miraglia et al. 2009).

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

28

#### 29 **5.2.4.2 Impacts on food quality**

30 There are two main routes by which food quality may change. First, the direct effects of climate  
31 change on plant and animal biology, such as through changing temperatures changing the basic  
32 metabolism of plants. Secondly, by increasing carbon dioxide's effect on biology through CO<sub>2</sub>  
33 fertilisation.

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

45 *Effects of rising CO<sub>2</sub> concentrations.* Climate change is being driven by rising concentrations of  
46 carbon dioxide and other greenhouse gases in the atmosphere. As plants use CO<sub>2</sub> in photosynthesis to



1 form sugar, rising CO<sub>2</sub> levels, all things being equal, enhances the process unless limited by water or  
2 nitrogen availability. This is known as “CO<sub>2</sub> fertilisation”. Furthermore, increasing CO<sub>2</sub> allows the  
3 stomata to be open for a shorter period for gas exchange, reducing water loss through transpiration.  
4 These two factors affect the metabolism of plants, and, as with changing temperatures, affects plant  
5 growth rates, yields and their nutritional quality. Studies of these effects include meta-analyses,  
6 modelling, and small-scale experiments (Franzaring et al. 2013; Mishra and Agrawal 2014; Myers et  
7 al. 2014; Ishigooka et al. 2017; Zhu et al. 2018; Loladze 2014; Yu et al. 2014)

8 In regard to nutrient quality, a meta-analysis from seven Free-Air Carbon dioxide Enrichment  
9 (FACE), (with elevated atmospheric CO<sub>2</sub> concentration of 546–586 ppm) experiments (Myers et al.  
10 2014), found that wheat grains had 9.3% lower zinc (CI 5.9–12.7%), 5.1% lower iron (CI 3.7–6.5%)  
11 and 6.3% lower protein (CI 5.2–7.5%), and rice grains had 7.8% lower protein content (CI 6.8–8.9%).  
12 Changes in nutrient concentration in field pea, soybean and C4 crops such as sorghum and maize were  
13 small or insignificant. Zhu et al. (2018) report a meta-analysis of FACE trials on a range of rice  
14 cultivars. They show that protein declines by an average of 10% under elevated CO<sub>2</sub>, iron and zinc  
15 decline by 8% and 5% respectively. Furthermore, a range of vitamins show large declines across all  
16 rice cultivars, including B1 (-17%), B2 (-17%), B5 (-13%) and B9 (-30%), whereas Vitamin E  
17 increased. As rice underpins the diets of many of the world’s poorest people in low-income countries,  
18 especially in Asia, Zhu et al. (2018) estimate that these changes under high CO<sub>2</sub> may affect the  
19 nutrient status of about 600 million people.

20 Decreases in protein concentration with elevated CO<sub>2</sub> are related to reduced nitrogen concentration  
21 possibly caused by nitrogen uptake not keeping up with biomass growth, an effect called  
22 ‘carbohydrate dilution’ or ‘growth dilution’, and by inhibition of photorespiration which can provide  
23 much of the energy used for assimilating nitrate into proteins (Bahrami et al. 2017). Other  
24 mechanisms have also been postulated (Feng et al. 2015; Bloom et al. 2014; Taub and Wang 2008).  
25 Together, the impacts on protein availability may take as many as 150 million people into protein  
26 deficiency by 2050 (Medek et al. 2017). Legume and vegetable yields increased with elevated CO<sub>2</sub>  
27 concentration of 250 ppm above ambient by 22% (CI 11.6–32.5%), with a stronger effect on leafy  
28 vegetables than on legumes and no impact for changes in iron, vitamin C or flavonoid concentration  
29 (Scheelbeek et al. 2018).

30 Increasing concentrations of atmospheric CO<sub>2</sub> lower the content of zinc and other nutrients in  
31 important food crops. Dietary deficiencies of zinc and iron are a substantial global public health  
32 problem (Myers et al. 2014). An estimated two billion people suffer these deficiencies (FAO 2013a),  
33 causing a loss of 63 million life-years annually (Myers et al. 2014). Most of these people depend on  
34 C3 grain legumes as their primary dietary source of zinc and iron. Zinc deficiency is currently  
35 responsible for large burdens of disease globally, and the populations who are at highest risk of zinc  
36 deficiency receive most of their dietary zinc from crops (Myers et al. 2015). The total number of  
37 people estimated to be placed at new risk of zinc deficiency by 2050 is 138 million. The people likely  
38 to be most affected live in Africa and South Asia, with nearly 48 million residing in India alone.  
39 Differences between cultivars of a single crop suggest that breeding for decreased sensitivity to  
40 atmospheric CO<sub>2</sub> concentration could partly address these new challenges to global health (Myers et  
41 al. 2014).

42 In summary, while increased CO<sub>2</sub> is projected to be beneficial for crop productivity at lower  
43 temperature increases, it is projected to lower nutritional quality (e.g., less protein, zinc, and iron)  
44 (*high confidence*).

45

## 1 **5.2.5 Climate change impacts on food stability**

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

5

### 6 **5.2.5.1 Impacts of extreme events**

7 FAO et al. (2018) conducted an analysis of prevalence of undernourishment (PoU) and found that in  
8 2017, the average of the prevalence of undernourishment (PoU) was 15.4% for all countries exposed  
9 to climate extremes (See Supplementary Material Figure SM5.2). At the same time, the PoU was 20%  
10 for countries that additionally show high vulnerability of agriculture production/yields to climate  
11 variability, or 22.4% for countries with high PoU vulnerability to severe drought. When there is both  
12 high vulnerability of agriculture production/yields and high PoU sensitivity to severe drought, the  
13 PoU is 9.8 points higher (25.2%). These vulnerabilities were found to be higher when countries had a  
14 high dependence on agriculture as measured by the number of people employed in the sector.  
15 Bangkok experienced severe flooding in 2011-2012 with large-scale disruption of the national food  
16 supply chains since they were centrally organised in the capital city (Allen et al. 2017).

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

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

28

### 29 **5.2.5.2 Food aid**

30 Food aid plays an important role in providing food security and saving lives after climate disasters. In  
31 2015, 14.5 million people were assisted through disaster-risk reduction, climate change and/or  
32 resilience building activities (WFP 2018). However, there is no agreement on how to better use  
33 emergency food aid, since it can come with unintended consequences for individuals, groups, regions,  
34 and countries (Barrett 2006). These may include negative dependency of food recipients (Lentz et al.  
35 2005) or price increases, among others.

36 Some authors state that tied food aid provided as “in kind” by the donor country hampers local food  
37 production (Clay 2006), although others found no evidence of this (Ferrière and Suwa-Eisenmann  
38 2015). Untied cash aid can be used to buy food locally or in neighbouring countries, which is cheaper  
39 and can contribute to improving the livelihoods of local farmers (Clay 2006).

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

44 In summary, based on AR5 and SR15 assessments that the likelihood that extreme weather will  
45 increase, (e.g., increases in heatwaves, droughts, inland and coastal flooding due to sea level rise

1 depending on region) in both frequency and magnitude, decreases in food stability and thus increases  
2 in food insecurity will likely rise as well (*medium evidence, high agreement*).

### 4 **5.3 Adaptation options, challenges, and opportunities**

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

#### 13 **5.3.1 Challenges and opportunities**

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

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

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

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

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

## 1 **Box 5.2 Sustainable solutions for food systems and climate change in Africa**

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

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

14 Commodity-based systems—driven by external markets—are increasing in Africa (cotton, cocoa,  
 15 coffee, oil palm, groundnuts) with important impacts on the use of land and climate. Land  
 16 degradation, decreasing water resources, loss of biodiversity, excessive use of synthetic fertilisers and  
 17 pesticides are some of the environmental challenges that influence preparedness to adapt to climate  
 18 change (Pretty and Bharucha 2015).

19 A balanced strategy on African agriculture can be based on SLM and multifunctional land use  
 20 approaches combining food production, cash crops, ecosystem services, biodiversity conservation,  
 21 and ecosystem services delivery, and indigenous and local knowledge.

22 Thus, sustainable food systems in Africa entail multiple dimensions as shown in Figure 5.7.



24  
 25 **Figure 5.7 Factors influencing sustainable food systems in Africa**

26 With rapid urbanisation, it is important to use combined land goals (e.g., zero-carbon energy, smart  
 27 irrigation systems, and climate-resilient agriculture) to minimise the negative side effects of climate  
 28 change while securing quality food for a growing population.

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

31 1) Closing yield gaps through adapted cultivars, sustainable land management, that  
 32 combine production and preservation of ecosystems essential functions such as sustainable

1 intensification approaches based on conservation agriculture and community-based adaptation with  
2 functioning support services and market access (Mbow et al. 2014a).

3 2) Identifying Sustainable Land Management practices (agroecology, agroforestry, etc.)  
4 addressing different ecosystem services (food production, biodiversity, reduction of GHG emissions,  
5 soil carbon sequestration) for improved land-based climate change adaptation and mitigation (Sanz et  
6 al. 2017; Francis 2016).

7 3) Paying attention to the food-energy-water nexus, especially water use and  
8 reutilisation efficiency but also management of rain water (Albrecht et al. 2018).

9 4) Implementing institutional designs focused on youth, women through new economic  
10 models that help access credit and loans to support policies that balance cash and food crops.

11 5) Build on and use of local knowledge, culture and traditions while seeking innovations  
12 for food waste reduction and transformation of agricultural products.

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

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

## 21 **5.3.2 Adaptation framing and key concepts**

### 22 **5.3.2.1 Autonomous, incremental, and transformational adaptation**

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

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

34 *Incremental.* Incremental adaptation maintains the essence and integrity of a system or process at a  
35 given scale (Park et al. 2012). Incremental adaptation focuses on improvements to existing resources  
36 and management practices. The central aim of incremental adaptation is to maintain the essence and  
37 integrity of a system or process at a given scale (IPCC 2014a).

38 *Transformational.* Transformational adaptation changes the fundamental attributes of a socio-  
39 ecological system either in anticipation of or in response to climate change and its impacts (IPCC  
40 2014a). Transformational adaptation seeks alternative livelihoods and land use strategies needed to  
41 develop new farming systems (Termeer et al. 2016). For example, limitations in incremental  
42 adaptation among smallholder rice farmers in Northwest Costa Rica led to a shift from rice to  
43 sugarcane production due to decreasing market access and water scarcity (Warner et al. 2015).  
44 Migration from the Oldman River Basin has been described as a transformational adaptation to climate

1 change in the Canadian agriculture sector (Hadarits et al. 2017). If high-end scenarios of climate  
 2 change eventuate, the food security of farmers and consumers will depend on how transformational  
 3 change in food systems is managed. An integrated framework of adaptive transition – management of  
 4 socio-technical transitions and adaptation to socio-ecological changes – may help build  
 5 transformational adaptive capacity (Mockshell and Kamanda 2018; Pant et al. 2015). Rippke et al.  
 6 (2016) has suggested overlapping phases of adaptation needed to support transformational change in  
 7 Africa.

8  
 9 **Table 5.3 Synthesis of food security related adaptation options to address various climate risks (IPCC**  
 10 **2014b; Vermeulen et al. 2013, 2018; Burnham and Ma 2016; Bhatta and Aggarwal 2016)**

<b>Key climate drivers and risks</b>	<b>Incremental adaptation</b>	<b>Transformational adaptation</b>	<b>Enabling conditions</b>
<p>Extreme events and short-term climate variability</p> <p>Stress on water resources, drought stress, dry spells, heat extremes, flooding, shorter rainy seasons, pests</p>	<ul style="list-style-type: none"> <li>- Change in variety, water management, water harvesting, supplemental irrigation during dry spells,</li> <li>- Planting dates, pest control, feed banks,</li> <li>- Transhumance, Other sources of revenue (e.g. charcoal, wild fruits, wood, temporary work)</li> <li>- Soil management, composting,</li> </ul>	<ul style="list-style-type: none"> <li>- Early Warning Systems</li> <li>- Use of planning and prediction at seasonal to intra-seasonal climate risk to transition to a food safer condition.</li> <li>- Abandonment of monoculture, diversification</li> <li>- Crop and livestock insurance</li> <li>- Alternate cropping, intercropping</li> <li>-Erosion control</li> </ul>	<ul style="list-style-type: none"> <li>- Establishment of climate services</li> <li>- Integrated water management policies, integrated land and water governance</li> <li>- Seed banks, seed sovereignty and seed distribution policies</li> <li>- Capacity building and extension programs</li> </ul>
<p>Warming trend, drying trend</p> <p>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</p>	<ul style="list-style-type: none"> <li>- Strategies to reduce effects of recurring food challenges</li> <li>- Sustainable intensification, agroforestry, conservation agriculture, SLM</li> <li>- Adoption of existing drought-tolerant crop and livestock species</li> <li>- Counter season crop production,</li> <li>- Livestock fattening</li> <li>- New ecosystem-based adaptation (e.g. bee keeping, woodlots)</li> </ul>	<ul style="list-style-type: none"> <li>- Climate services for new agricultural programs, e.g., sustainable irrigation districts)</li> <li>- New technology, e.g., new farming systems, new crops and livestock breeds</li> <li>- Switches between cropping and transhumant livelihoods, replacement of pasture or forest to irrigated/rainfed crops</li> <li>- Shifting to small ruminants or drought resistant livestock or fish</li> </ul>	<ul style="list-style-type: none"> <li>- Climate information in local development policies.</li> <li>- Stallholders' access to credit and production resources,</li> <li>- National food security program based on increased productivity, diversification, transformation and trade</li> <li>- Strengthening (budget, capacities, expertise) of local and national institutions to support agriculture and</li> </ul>

	<ul style="list-style-type: none"> <li>- Farmers management of natural resources</li> <li>- Labor redistribution (e.g., mining, development projects, urban migration)</li> <li>- Adjustments to markets and trade pathways already in place</li> </ul>	<ul style="list-style-type: none"> <li>farming</li> <li>Food storage infrastructures, food transformation</li> <li>- Changes in cropping area, land rehabilitation (enclosures, afforestation) perennial farming</li> <li>- New markets and trade pathways</li> </ul>	<ul style="list-style-type: none"> <li>livestock breeding</li> <li>- Devolution to local communities, women empowerment, market opportunities</li> <li>- Incentives for establishing new markets and trade pathways</li> </ul>
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1

2 **5.3.2.2 Risk management**

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

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

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

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

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

31 In many countries, governmental compensation for crop-failure and financial losses are used to  
32 protect against risk of severe yield reductions. Both public and private sector groups develop  
33 insurance markets and improve and disseminate index-based weather insurance programs.

1 Catastrophe bonds, microfinance, disaster contingency funds, and cash transfers are other available  
2 mechanisms for risk management.

3 In summary, risk management can be accomplished through agro-ecological landscape approaches  
4 and risk sharing and transfer mechanisms such as development of insurance markets and improve  
5 index-based weather insurance programs (*high confidence*).

6

### 7 **5.3.2.3 Role of agroecology and diversification**

8 Agro-ecological systems are integrated land-use systems that maintain species diversity in a range of  
9 productive niches. Diversified cropping systems and practicing traditional agro-ecosystems of crop  
10 production where a wide range of crop varieties are grown in various spatial and temporal  
11 arrangements, are less vulnerable to catastrophic loss (Zhu et al. 2011). The use of local genetic  
12 diversity, soil organic matter enhancement, multiple-cropping or poly-culture systems, and home  
13 gardening, agro-ecological approaches can build resilience against extreme climate events (Altieri and  
14 Koohafkan 2008). However, Nie et al. (2016) argued that while integrated crop-livestock systems  
15 present some opportunities such as control of weeds, pests and diseases, and environmental benefits,  
16 there are some challenges, including yield reduction, difficulty in pasture-cropping, grazing, and  
17 groundcover maintenance in high rainfall zones, and development of persistent weeds and pests.  
18 Adaptation measures based on agroecology entail enhancement of agrobiodiversity; improvement of  
19 ecological processes and delivery of ecosystem services. They also entail strengthening of local  
20 communities and recognition of the role and value of indigenous and local knowledge. Such practices  
21 can enhance the sustainability and resilience of agricultural systems by buffering climate extremes,  
22 reducing degradation of soils, and reversing unsustainable use of resources; outbreak of pests and  
23 diseases and consequently increase yield without damaging biodiversity. Increasing and conserving  
24 biological diversity such as soil microorganisms can promote high crop yields and sustain the  
25 environment (Schmitz et al 2015; Bhattacharyya et al 2016; Garibaldi et al 2017).

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

31 The more diverse the food systems are, the more resilient they are in enhancing food security in the  
32 face of biotic and abiotic stresses. Diverse production systems are important for providing regulatory  
33 ecosystem services such as nutrient cycling, carbon sequestration, soil erosion control, reduction of  
34 GHG emissions and control of hydrological processes (Chivenge et al. 2015). Further options for  
35 adapting to change in both mean climate and extreme events are livelihood diversification (Michael  
36 2017; Ford et al. 2015), and production diversity (Sibhatu et al. 2015).

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

44 Evidence also shows that, together with other factors, on-farm agricultural diversity can translate into  
45 dietary diversity at the farm level and beyond (Pimbert and Lemke 2018; Kumar et al. 2015; Sibhatu  
46 et al. 2015). Dietary diversity is important but not enough as an adaptation option, but results in



1 positive health outcomes by increasing the variety of healthy products in people's diets and reducing  
2 exposure to unhealthy environments.

3 Locally developed seeds and the concept of seed sovereignty can both help protect local  
4 agrobiodiversity and can often be more climate resilient than generic commercial varieties (Watt  
5 2016; Coomes et al., 2015; van Niekerk and Wynberg 2017; Vasconcelos et al. 2013). Seed exchange  
6 networks and banks protect local agrobiodiversity and landraces, and can provide crucial lifelines  
7 when crop harvests fail (Coomes et al. 2015; van Niekerk and Wynberg 2017; Vasconcelos et al.  
8 2013).

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

14

### 15 **Box 5.3 Climate change and indigenous food systems in the Hindu-Kush Himalayan** 16 **Region**

17 Diversification of production systems through promotion of Neglected and Underutilised Species  
18 (NUS; also known as understudied, neglected, orphan, lost or disadvantaged crops) offers adaptation  
19 opportunities to climate change, particularly in mountains. Neglected and Underutilised Species  
20 (NUS) have a potential to improve food security and at the same time help protect and conserve  
21 traditional knowledge and biodiversity. Scaling-up NUS requires training farmers and other  
22 stakeholders on ways to adopt adequate crop management, quality seed, select varieties, farming  
23 systems, soil management, development of new products, and market opportunities (Padulosi et al.  
24 2013). Farmers in the Rasuwa district, in the mid-hills of Nepal, prefer to cultivate local bean, barley,  
25 millet and local maize, rather than commodity crops because they are more tolerant to water stress and  
26 extremely cold conditions (Adhikari et al. 2017). Farmers in the high-altitude cold climate of Nepal  
27 prefer local barley with its short growing period because of a shorter growing window. Buckwheat is  
28 commonly grown in the Hindu-Kush Himalayan (HKH) region mainly because it grows fast and  
29 suppresses weeds. In Pakistan, quinoa (*Chenopodium quinoa*) grew and produced well under saline  
30 and marginal soil where other crops would not grow (Adhikari et al. 2017).

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

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

44 However, transition from traditional diets based on local foods to a commercial crop-based diet with  
45 high fats, salt, sugar and processed foods, increased the incidence of non-communicable diseases,  
46 such as diabetes, obesity, heart diseases and certain types of cancer (Abarca-Gómez et al. 2017; NCD-

1 RisC 2016b, 2017b). This ‘hidden hunger’ – enough calories, but insufficient vitamins - is  
2 increasingly evident in mountainous communities including the HKH region.

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

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

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

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

31  
32 Dietary diversity has also been correlated (*medium evidence, medium agreement*) to agricultural  
33 diversity in small-holder and subsistence farms (Ayenew et al. 2018; Jones et al. 2014; Jones 2017;  
34 Pimbert and Lemke 2018), including both crops and animals, and has been proposed as a strategy to  
35 reduce micronutrient malnutrition in developing countries (Tontisirin et al. 2002). In this regard, the  
36 capacity of subsistence farming to supply essential nutrients in reasonable balance to the people  
37 dependent on them has been considered as a means of overcoming their nutrient limitations in sound  
38 agronomic and sustainable ways (Graham et al. 2007).

39 *Ecosystem-based adaptation (EbA)*. EbA is a set of nature-based methods addressing climate change  
40 adaptation and food security by strengthening and conserving natural functions, goods and services  
41 that benefit to people. EbA approaches to address food security provide co-benefits such as  
42 contributions to health and improved diet, sustainable land management, economic revenue and water  
43 security. EbA practices can reduce greenhouse gas emissions and increase carbon storage (USAID  
44 2017).

45 For example, agroforestry systems can contribute to improving food productivity while enhancing  
46 biodiversity conservation, ecological balance and restoration under changing climate conditions

1 (Mbow et al. 2014a; Paudela et al. 2017; Newaj et al. 2016; Altieri et al. 2015). Agroforestry systems  
2 have been shown to reduce erosion through their canopy cover and their contribution to the micro-  
3 climate and erosion control (Sida et al. 2018). Adoption of conservation farming practices such as  
4 removing weeds from and dredging irrigation canals, draining and levelling land, and using organic  
5 fertilisation were among the popular conservation practices in small-scale paddy rice farming  
6 community of northern Iran (Ashoori and Sadegh 2016).

7 Adaptation potential of ecologically-intensive systems includes also forests and rivers ecosystems,  
8 where improved resources management such as soil conservation, water cycling and agro-biodiversity  
9 support the function of food production affected by severe climate change (Muthee et al. 2017). The  
10 use of non-crop plant resources in agro-ecosystems (permaculture, perennial polyculture) can improve  
11 ecosystem conservation and may lead to increased crop productivity (Balzan et al. 2016; Crews et al.  
12 2018; Toensmeier 2016).

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

#### 19 **5.3.2.4 Role of cultural values**

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

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

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

44 Culturally sensitive risk analysis can deliver a better understanding of what climate change means for  
45 society (O'Brien and Wolf 2010; Persson et al. 2015) and thus, how to better adapt. Murphy et al.  
46 (2016) stated that culture and beliefs play an important role in adaptive capacity but that they are not

1 static. In the work done by Elum et al. (2017) in South Africa about farmers perception of climate  
2 change, they concluded that perceptions and beliefs often have negative effects on adaptation options.

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

### 13 **5.3.3 Supply-side adaptation**

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

#### 17 **5.3.3.1 Crop production**

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

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

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

39 Water management is another key area for adaptation. Increasing water availability and reliability of  
40 water for agricultural production using different techniques of water harvesting, storage, and its  
41 judicious utilisation through farm ponds, dams, and community tanks in rainfed agriculture areas have  
42 been presented by Rao et al. (2017) and Rivera-Ferre et al. (2016a). In addition, improved drainage  
43 systems (Thiel et al. 2015), and Alternate Wetting and Drying (AWD) techniques for rice cultivation  
44 (Howell et al. 2015; Rahman and Bulbul 2015) have been proposed. Efficient irrigation systems have  
45 been also analysed and proposed by (Jägermeyr et al. 2016) Naresh et al (2017) (Gunarathna et al.

1 2017; Chartzoulakis and Bertaki 2015). Recent innovation includes using farming system with low  
2 usage of water such as drip-irrigation or hydroponic systems mostly in urban farming.

### 3 4 **5.3.3.2 Livestock production systems**

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

### 17 18 **5.3.3.3 Aquaculture, fisheries, and agriculture interactions**

19 Options may include livelihood diversification within and across sectors of fisheries, aquaculture and  
20 agriculture. Thus, adaptation options need to provide management approaches and policies that build  
21 the livelihood asset base, reducing vulnerability to multiple stressors with a multi-sector perspective  
22 (Badjeck et al. 2010). In Bangladesh fishing pressure on post-larval prawns has increased as displaced  
23 farmers have shifted to fishing following salt-water intrusion of agricultural land (Ahmed et al. 2013).  
24 In West Africa, strategies to cope with sudden shifts in fisheries are wider-reaching and have included  
25 turning to seafood import (Gephart et al. 2017) or terrestrial food production including farming and  
26 bush-meat hunting on land (Brashares et al. 2004). Proposed actions for adaptation include effective  
27 governance, improved management and conservation, efforts to maximise societal and environmental  
28 benefits from trade, increased equitability of distribution and innovation in food production, and the  
29 continued development of low-input and low-impact aquaculture (FAO 2018c).

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

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

#### 1 **5.3.3.4 Transport and storage**

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

4 *Transport.* One transport example is found in Bangkok. Between mid-November 2011 and early  
5 January 2012, Bangkok, the capital city of Thailand, faced its most dramatic flood in approximately  
6 70 years with most transport networks cut-off or destroyed. This caused large-scale disruption of the  
7 national food supply chains since they were centrally organised in the capital city (Allen et al. 2017).  
8 From this experience, the construction and management of ‘climate-proof’ rural roads and transport  
9 networks is argued as one the most important adaptation strategies for climate change and food  
10 security in Thailand (Rattanachot et al. 2015).

11 Similarly in Africa, it has been shown that enhanced transportation networks combined with other  
12 measures could reduce the impact of climate change on food and nutrition security (Brown et al.  
13 2017b). This suggests that strengthening infrastructure and logistics for transport would significantly  
14 enhance resilience to climate change while improving food and nutrition security in developing  
15 counties.

16 *Storage.* Storage refers to both structures and technologies for storing seed as well as produce.  
17 Predominant storage methods used in Uganda are single-layer woven polypropylene bags (popularly  
18 called “kavera” locally), chemical insecticides and granaries. Evidence from Omotilewa et al. (2018)  
19 showed that the introduction of new storage technology called Purdue Improved Crop Storage (PICS)  
20 could contribute to climate change adaptation. PICS is a chemical-free airtight triple-layered  
21 technology consisting of two high-density polyethylene inner liners and one outer layer of woven  
22 polypropylene bag. Its adoption has increased the number of households planting hybrid maize  
23 varieties that are more susceptible to insect pests in storage than traditional lower-yielding varieties.  
24 Such innovations could help to protect crops more safely and for longer periods from postharvest  
25 insect pests that are projected to increase as result of climate change, thus contributing to food  
26 security. In the Indo-Gangetic Plains many different storage structures based on ILK provide reliable  
27 and low-cost options made of local materials. For example, elevated grain stores protect from floods,  
28 but also provide for air circulation to prevent rot and to control insects and other vermin (Rivera-Ferre  
29 et al. 2013).

30

#### 31 **5.3.3.5 Trade and processing**

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

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

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

1 (2016) and Ali et al. (2018) as new advances in processing and packaging fruits, vegetables, meats,  
2 seafood, dairy, and egg products.

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

9

#### 10 **5.3.4 Demand-side adaptation**

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

20 The implications of dietary choice can have severe consequences for land. For example, Alexander et  
21 al. 2016, found that if every country were to adopt the UK's 2011 average diet and meat consumption,  
22 95% of global habitable land area would be needed for agriculture – up from 50% of land currently  
23 used. For the average US diet, 178% of global land would be needed (relative to 2011) (Alexander et  
24 al. 2016); and for “business as usual” dietary trends and existing rates of improvement in yields, 55%  
25 more land would be needed above baseline (2009) (Bajželj et al. 2014). Changing dietary habits has  
26 been suggested as an effective food route to affect land use (Beheshti et al. 2017) and promote  
27 adaptation to climate change through food demand.

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

36 Reduction in the demand for animal-based food products and increasing proportions of plant-based  
37 foods in diets, particularly pulses and nuts; and replacing red meat with other more-efficient protein  
38 sources are demand-side adaptation measures (Machovina et al. 2015) (see also Section 5.5.2). For  
39 example, replacing beef in the US diet with poultry can meet caloric and protein demands of about  
40 120 to 140 million additional people consuming the average American diet (Shepon et al. 2016).  
41 Similar suggestions are made for adopting the benefits of moving to plant-based protein, such as  
42 beans (Harwatt et al. 2017).

43 The main reason why reducing meat consumption is an adaptation measure is because it reduces  
44 pressure on land and water and thus our vulnerability to climate change and inputs limitations  
45 (Vanham et al. 2013). For animal feed, ruminants can have positive ecological effects (species  
46 diversity, soil carbon) if they are fed extensively on existing grasslands. Similarly, reducing waste at

1 all points along the entire food chain is a significant opportunity for improving demand-side  
2 adaptation measures (Godfray 2015).

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

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

11

### 12 **5.3.5 Institutional measures**

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

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

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

39

#### 40 **5.3.5.1 Global initiatives**

41 Climate change poses serious wide-ranging risks, requiring a broader approach in fighting the  
42 phenomenon. The United Nations Framework Convention on Climate Change (UNFCCC) and its  
43 annual Conferences of the Parties (COPs) has been instrumental in ensuring international cooperation  
44 in the field of tackling the impacts of climate change in a broader framework (Cléménçon 2016). The  
45 National Adaptation Plan (NAP) program under the UNFCCC, was established to: identify vulnerable  
46 regions; assess the impacts of climate change on food security; and prioritise adaptation measures for



1 implementation to increase resilience. The National Adaptation Programs of Action (NAPAs) was  
2 also established to support least-developed countries (LDCs) address their particular challenges in  
3 adaptation, to enhance food security among other priorities. The Paris Agreement (UNFCCC 2015) is  
4 a major victory for small island states and vulnerable nations that face climate change-related impacts  
5 of floods and droughts resulting in food security challenges. Adaptation and mitigation targets set by  
6 the parties through their nationally determined commitments (NDCs) are reviewed internationally to  
7 ensure consistency and progress towards actions (Falkner 2016).

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

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

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

### 31 32 **5.3.5.2 National policies**

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

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

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

1 and Naranpanawa 2016). Enhancement of representation, democratic and inclusive governance, as  
2 well as equity and fairness for improving climate change adaptation policy processes and outcomes in  
3 Nepal were also suggested as intuitional measure by Ojha et al. (2015). Further, food, nutrition, and  
4 health policy adaptation options such as social safety nets and social protection have been  
5 implemented in India, Pakistan, Middle East and North Africa (Devereux 2015; Mumtaz and  
6 Whiteford 2017; Narayanan and Gerber 2017).

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

12

### 13 **5.3.5.3 Community-based adaptation**

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

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

27 Community-based adaptation generates strategies through participatory processes, involving local  
28 stakeholders and development and disaster risk–reduction practitioners. Fostering collaboration and  
29 community stewardship is central to the success of CBA (Scott et al. 2017). Preparedness behaviours  
30 that are encouraged include social connectedness, education, training, and messaging; CBA also can  
31 encompass beliefs that might improve household preparedness to climate disaster risk (Thomas et al.  
32 2015). Reliance on social networks, social groups connectivities, or moral economies reflect the  
33 importance of collaboration within communities (Reuter 2018; Schramski et al. 2017).

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

42 With these considerations, community-based adaptation can help to link local adaptation with  
43 international development and climate change policies (Forsyth 2013). In developing CBA programs,  
44 barriers exist that may hinder implementation. These include poor coordination within and between  
45 organisations implementing adaptation options, poor skills, poor knowledge about climate change,  
46 and inadequate communication among stakeholders (Spires et al. 2014). A rights-based approach has

1 been suggested to address issues of equality, transparency, accountability and empowerment in  
2 adaptation to climate change (Ensor et al. 2015).

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

8

### 9 **5.3.6 Tools and finance**

#### 10 **5.3.6.1 Early Warning Systems**

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

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

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

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

39

#### 40 **5.3.6.2 Financial resources**

41 Financial instruments such as micro-insurance, index-based insurance, provision of post-disaster  
42 finances for recovery and pre-disaster payment are fundamental means to reduce lower and medium  
43 level risks (Linnerooth-Bayer and Hochrainer-Stigler 2014). Fenton & Paavola, 2015; Dowla, 2018).  
44 Hammill et al. (2010) found that microfinance services (MFS) are especially helpful for the poor.  
45 MFS can provide poor people with the means to diversify, accumulate and manage the assets needed  
46 to become less susceptible to shocks and stresses. As a result, MFS plays an important role in

1 vulnerability reduction and climate change adaptation among some of the poor. The provision of  
2 small-scale financial products to low-income and otherwise disadvantaged groups by financial  
3 institutions can serve as adaptation to climate change. Access to finance in the context of climate  
4 change adaptation that focuses on poor households and women in particular is bringing encouraging  
5 results (Agrawala and Carraro 2010).

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

## 15 **5.4 Impacts of food systems on climate change**

### 16 **5.4.1 Greenhouse gas emissions from food systems**

17 This chapter assesses the contributions of the entire food system to greenhouse gas (GHG) emissions.  
18 Food systems emissions include CO<sub>2</sub> and non-CO<sub>2</sub> gases, specifically those generated from: i) crop  
19 and livestock activities within the farm gate (Table 5.4, category ‘Agriculture’); ii) land use and land  
20 use change dynamics associated with agriculture (Table 5.4, category ‘Land Use’); and iii) food  
21 processing, retail and consumption patterns, including upstream and downstream processes such as  
22 manufacture of chemical fertilisers and fuel (Table 5.4, category ‘Beyond Farm Gate’). The first two  
23 categories comprise emissions reported by countries in the AFOLU (Agriculture, Forestry, and Other  
24 Land Use) sectors of national GHG inventories; the latter comprises emissions reported in other  
25 sectors of the inventory, as appropriate, for instance, industrial processes, energy use, and food loss  
26 and waste.

27 The first two components (agriculture and land use) identified above are well quantified and  
28 supported by an ample body of literature (Smith et al. 2014). During the period 2007-2016, global  
29 agricultural non-CO<sub>2</sub> emissions from crop and livestock activities within the farm gate were  $6.2 \pm 1.9$   
30 Gt CO<sub>2</sub>-eq yr<sup>-1</sup> during 2007-2016, with methane ( $142 \pm 43$  Mt CH<sub>4</sub> yr<sup>-1</sup>, or  $4.1 \pm 1.2$  Gt CO<sub>2</sub>-eq yr<sup>-1</sup>)  
31 contributing in CO<sub>2</sub>eq about twice as much as nitrous oxide ( $8.3 \pm 2.3$  Mt N<sub>2</sub>O yr<sup>-1</sup>, or  $2.1 \pm 0.6$  Gt  
32 CO<sub>2</sub>-eq yr<sup>-1</sup>) to this total (see Table 2.2 in Chapter 2). Emissions from land use associated with  
33 agriculture in some regions, such as from deforestation and peatland degradation (both processes  
34 involved in preparing land for agricultural use), added globally during the same period another  $4.8 \pm$   
35  $2.4$  Gt CO<sub>2</sub>-eq yr<sup>-1</sup> (see Chapter 2). These estimates are associated with uncertainties of about 30%  
36 (agriculture) and 50% (land use), as per IPCC AR5 (Smith et al. 2014).

37 Agriculture activities within the farm gate and associated land use dynamics are therefore responsible  
38 for about  $11.0 \pm 3.1$  Gt CO<sub>2</sub>-eq yr<sup>-1</sup>, or some 20% of total anthropogenic emissions (Table 5.4),  
39 consistent with post-AR5 findings (e.g., Tubiello et al. (2015)). In terms of individual gases, the  
40 contributions of agriculture to total emissions by gas are significantly larger. For instance, over the  
41 period 2010-2016, methane gas emissions within the farm gate represented about half of the total CH<sub>4</sub>  
42 emitted by all sectors, while nitrous dioxide gas emissions within the farm gate represented about  
43 three-quarters of the total N<sub>2</sub>O emitted by all sectors (Tubiello 2019). In terms of carbon, CO<sub>2</sub>

1 emissions from deforestation and peatland degradation linked to agriculture contributed about 10% of  
2 the CO<sub>2</sub> emitted by all sectors in 2017 (Le Quéré et al. 2018).

3 Food systems emissions beyond the farm gate, such as those upstream from manufacturing of  
4 fertilisers, or downstream such as food processing, transport and retail, and food consumption,  
5 generally add to emissions from agriculture and land use, but their estimation is very uncertain due to  
6 lack of sufficient studies. The IPCC AR5 (Fischedick et al. 2014) provided some information on these  
7 other food system components, noting that emissions beyond the farm gate in developed countries  
8 may equal those within the farm gate, and cited one study estimating world total food system  
9 emissions to be up to 30% of total anthropogenic emissions (Garnett 2011). More recently, Poore and  
10 Nemecek (2018), by looking at a database of farms and using a combination of modelling approaches  
11 across relevant processes, estimated a total contribution of food systems around 26% of total  
12 anthropogenic emissions. Total emissions from food systems may thus account for 25-30% of total  
13 GHG emissions (*medium confidence*).

14 Based on the available literature, a break-down of individual contributions of food systems emissions  
15 is show in Table 5.4, between those from agriculture within the farm gate (10-12%) (*high confidence*);  
16 emissions from land use and land use change dynamics such as deforestation and peatland  
17 degradation, which are associated with agriculture in many regions (8-10%) (*high confidence*); and  
18 those from food supply chain activities past the farm gate, such as storage, processing, transport, and  
19 retail (5-10%) (*limited evidence, medium agreement*). Note that the corresponding lower range of  
20 emissions past the farm gate, i.e., 2.5 Gt CO<sub>2</sub>-eq yr<sup>-1</sup> (Table 5.4), is consistent with recent estimates  
21 made by Poore and Nemecek (2018). Contributions from food loss and waste are implicitly included  
22 in these estimates of total emissions from food systems (See Section 5.5.2.5). They may account for  
23 8–10% of total GHG emissions from agriculture and land use (FAO 2013b) (*low confidence*).

24

25 **Table 5.4 GHG emissions (Gt CO<sub>2</sub>eq yr<sup>-1</sup>) from the food system and their contribution (%) to total**  
26 **anthropogenic emissions. Mean of 2007-2016 period.**

Food system component	Emissions (Gt CO <sub>2</sub> eq yr <sup>-1</sup> )	Share in mean total emissions (%)
Agriculture	6.2 ± 1.9 <sup>a</sup>	10-12%
Land use	4.8 ± 2.4 <sup>a</sup>	8-10%
Beyond farm gate	3.8 ± 1.3 <sup>b</sup>	5-10%
Food system (Total)	14.8 ± 3.4	25-30%

27 Notes: Food system emissions are estimated by combining emissions data from a) FAOSTAT (2018) and US  
28 EPA (See also Chapter 2) and b) Garnett (2011) and Poore and Nemecek (2018). Percentage shares were  
29 computed by using a total emissions value for the period 2007-2016 of nearly 51 Gt CO<sub>2</sub>-eq yr<sup>-1</sup> (See Chapter 2).  
30 GWP values used are those , and by using GWP values of the IPCC AR5 with no climate feedback (GWP-  
31 CH4=28; GWP-N2O=265)..

32

### 33 **5.4.2 Greenhouse gas emissions from croplands and soils**

34 Since AR5, a few studies have quantified separate contributions of crops and soils on the one hand,  
35 and livestock on the other, to the total emissions from agriculture and associated land use. For  
36 instance, Carlson et al. (2017) estimated emissions from cropland to be in the range of 2–3 GtCO<sub>2</sub>-eq

1 yr<sup>-1</sup>, including methane emissions from rice, CO<sub>2</sub> emissions from peatland cultivation, and N<sub>2</sub>O  
 2 emissions from fertiliser applications. Data from FAOSTAT (2018), recomputed to use AR5 GWP  
 3 values, indicated that cropland emissions from these categories were 3.6 ± 1.2 Gt CO<sub>2</sub>-eq yr<sup>-1</sup> over the  
 4 period 2010–2016; two-thirds of this were related to peatland degradation, followed by N<sub>2</sub>O  
 5 emissions from synthetic fertilisers and methane emissions from paddy rice fields (Tubiello 2019).  
 6 These figures are a subset of the total emissions from agriculture and land use reported in Table 5.4.  
 7 Asia, especially India, China and Indonesia accounted for roughly 50% of global emissions from  
 8 croplands. Figure 5.8 shows the spatial distribution of emissions from cropland according to Carlson  
 9 et al. (2017), not including emissions related to deforestation or changes in soil carbon.

10



11

12 **Figure 5.8 Cropland GHGs consist of CH<sub>4</sub> from rice cultivation, CO<sub>2</sub>, N<sub>2</sub>O, and CH<sub>4</sub> from peatland**  
 13 **draining, and N<sub>2</sub>O from N fertiliser application. Total emissions from each grid cell are concentrated in**  
 14 **Asia, and are distinct from patterns of production intensity (Carlson et al. 2017).**

### 15 5.4.3 Greenhouse gas emissions from livestock

16 Emissions from livestock include non-CO<sub>2</sub> gases from enteric fermentation from ruminant animals  
 17 and from anaerobic fermentation in manure management processes, as well as non-CO<sub>2</sub> gases from  
 18 manure deposited on pastures (Smith et al. 2014). Estimates after the AR5 include those from Herrero  
 19 et al. (2016), who quantified non-CO<sub>2</sub> emissions from livestock to be in the range of 2.0–3.6 GtCO<sub>2</sub>-  
 20 eq yr<sup>-1</sup>, with enteric fermentation from ruminants being the main contributor. FAOSTAT (2018)  
 21 estimates of these emissions, renormalized to AR5 GWP values, were 4.1 ± 1.2 Gt CO<sub>2</sub>-eq yr<sup>-1</sup> over  
 22 the period 2010–2016.

23 These estimates of livestock emissions are for those generated within the farm gate. Adding emissions  
 24 from relevant land use change, energy use, and transportation processes, FAO (2014a) and Gerber et  
 25 al. (2013) estimated livestock emissions of up to 5.3 ± 1.6 GtCO<sub>2</sub>-eq yr<sup>-1</sup> circa the year 2010 (data  
 26 from original papers, but scaled to SAR global warming potential (GWP) values for methane, for  
 27 comparability with previous results).

28 All estimates agree that cattle are the main source of global livestock emissions (65–77%). Livestock  
 29 in low and middle-income countries contribute 70% of the emissions from ruminants and 53% from  
 30 monogastric livestock (animals without ruminant digestion processes such as sheep, goats, pigs, and  
 31 poultry), and these are expected to increase as demand for livestock products increases in these  
 32 countries (Figure 5.9). In contrast to the increasing trend in absolute GHG emissions, GHG emissions  
 33 intensities, defined as GHG emissions per unit produced, have declined globally and are about 60%  
 34 lower today than in the 1960s. This is largely due to improved meat and milk productivity of cattle  
 35 breeds (FAOSTAT 2018; Davis et al. 2015).

1 Still, products like red meat remain the most inefficient in terms of emissions per kg of protein  
2 produced in comparison to milk, pork, eggs and all crop products (IPCC 2014b). Yet, the functional  
3 unit used in these measurements is highly relevant and may produce different results (Salou et al.  
4 2017). For instance, metrics based on products tend to rate intensive livestock systems as efficient,  
5 while metrics based on area or resources used tend to rate extensive system as efficient (Garnett  
6 2011). In ruminant dairy systems, less intensified farms show higher emissions if expressed by  
7 product, and lower emissions if expressed by Utilizable Agricultural Land (Gutiérrez-Peña et al. 2019;  
8 Salvador et al. 2017; Salou et al. 2017).

9 Furthermore, if other variables are used in the analysis of GHG emissions of different ruminant  
10 production systems, such as human-edible grains used to feed animals instead of crop waste and  
11 pastures of marginal lands, or C sequestration in pasture systems in degraded lands, then the GHG  
12 emissions of extensive systems are reduced. Reductions of 26 and 43% have been shown in small  
13 ruminants, such as sheep and goats (Gutiérrez-Peña et al. 2019; Salvador et al. 2017; Batalla et al.  
14 2015; Petersen et al. 2013). In this regard, depending on what the main challenge is in different  
15 regions (e.g., undernourishment, overconsumption, natural resources degradation), different metrics  
16 could be used as reference. Other metrics that consider nutrient density have been proposed because  
17 they provide potential for addressing both mitigation and health targets (Doran-Browne et al. 2015).

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

22 Increases in economies of scale linked to increased efficiencies and decreased emission intensities  
23 may lead to more emissions, rather than less, an observed dynamic referred to by economists as a  
24 ‘rebound effect.’ This is because increased efficiency allows production processes to be performed  
25 using fewer resources and often at lower cost. This in turn influences consumer behaviour and product  
26 use, increasing demand and leading to increased production. In this way, the expected gains from new  
27 technologies that increase the efficiency of resource use may be reduced (i.e., increase in the total  
28 production of livestock despite increased efficiency of production due to increased demand for meat  
29 sold at lower prices). Thus, in order for the livestock sector to provide a contribution to GHG  
30 mitigation, reduction in emissions intensities need to be accompanied by appropriate governance and  
31 incentive mechanisms to avoid rebound effects, such as limits on total production.

32



33

34 **Figure 5.9 Global GHG emissions from livestock for 1995-2005 (Herrero et al. 2016a)**

35 Variation in estimates of N<sub>2</sub>O emissions are due to differing a) climate regimes, b) soil types, and c)  
36 N transformation pathways (Charles et al. 2017; Fitton et al. 2017). It was recently suggested that

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1 N<sub>2</sub>O soil emissions linked to livestock through manure applications could be 20%-40% lower than  
2 previously estimated in some regions, for instance in Sub-Saharan Africa and Eastern Europe (Gerber  
3 et al. 2016) and from smallholder systems in East Africa (Pelster et al. 2017). Herrero et al. (2016a)  
4 estimated global livestock enteric methane to range from 1.6–2.7 Gt CO<sub>2</sub>-eq, depending on  
5 assumptions of body weight and animal diet.

#### 6 7 **5.4.4 Greenhouse gas emissions from aquaculture**

8 Emissions from aquaculture and fisheries may represent some 10% of total agriculture emissions, or  
9 about 0.58 Gt CO<sub>2</sub>-eq yr<sup>-1</sup> (Barange et al. 2018), with two-thirds being non-CO<sub>2</sub> emissions from  
10 aquaculture (Hu et al. 2013; Yang et al. 2015) and the rest due to fuel use in fishing vessels. They  
11 were not included in Table 5.4 under agriculture emissions, as these estimates are not included in  
12 national GHG inventories and global numbers are small as well as uncertain.

13 Methodologies to measure aquaculture emissions are still being developed (Vasanth et al. 2016). N<sub>2</sub>O  
14 emissions from aquaculture are partly linked to fertiliser use for feed as well as aquatic plant growth,  
15 and depend on the temperature of water as well as on fish production (Paudel et al. 2015). Hu et al.  
16 (2012) estimated the global N<sub>2</sub>O emissions from aquaculture in 2009 to be 0.028 Gt CO<sub>2</sub>-eq yr<sup>-1</sup>, but  
17 could increase to 0.114 Gt CO<sub>2</sub>-eq yr<sup>-1</sup> (that is 5.72% of anthropogenic N<sub>2</sub>O–N emissions) by 2030 for  
18 an estimated 7.10% annual growth rate of the aquaculture industry. Numbers estimated by Williams  
19 and Crutzen (2010) were around 0.036 Gt CO<sub>2</sub>-eq yr<sup>-1</sup>, and suggested that this may rise to more than  
20 0.179 Gt CO<sub>2</sub>-eq yr<sup>-1</sup> within 20 years for an estimated annual growth of 8.7%. (Barange et al. 2018)  
21 assessed the contribution of aquaculture to climate change as 0.38 Gt CO<sub>2</sub>-eq yr<sup>-1</sup> in 2010, around 7%  
22 of those from agriculture.

23 CO<sub>2</sub> emissions coming from the processing and transport of feed for fish raised in aquaculture, and  
24 also the emissions associated with the manufacturing of floating cultivation devices (e.g., rafts or  
25 floating fish-farms), connecting or mooring devices, artificial fishing banks or reefs, and feeding  
26 devices (as well as their energy consumption) may be considered within the emissions from the food  
27 system. Indeed, most of the GHG emissions from aquaculture are associated with the production of  
28 raw feed materials and secondarily, with the transport of raw materials to mills and finished feed to  
29 farms (Barange et al. 2018).

#### 30 31 **5.4.5 Greenhouse gas emissions from inputs, processing, storage, and transport**

32 Apart from emissions from agricultural activities within the farm gate, food systems also generate  
33 emissions from the pre- and post-production stages in the form of input manufacturing (fertilisers,  
34 pesticides, feed production) and processing, storage, refrigeration, retail, waste disposal, food service,  
35 and transport. The total contribution of these combined activities outside the farm gate is not well  
36 documented. Based on information reported in the AR5 (Fischedick et al. 2014), we estimated their  
37 total contribution to be roughly 15% of total anthropogenic emissions (Table 5.4). There is no post-  
38 AR5 assessment at the global level in terms of absolute emissions. Rather, several studies have  
39 recently investigated how the combined emissions within and outside the farm gate are embedded in  
40 food products and thus associated with specific dietary choices (see next section). Below important  
41 components of food systems emissions beyond the farm gate are discussed based on recent literature.

42 Refrigerated trucks, trailers, shipping containers, warehouses, and retail displays that are vital parts of  
43 food supply chains all require energy and are direct sources of GHG emissions. Upstream emissions  
44 in terms of feed and fertiliser manufacture and downstream emissions (transport, refrigeration) in  
45 intensive livestock production (dairy, beef, pork) can account for up to 24–32% of total livestock  
46 emissions, with the higher fractions corresponding to commodities produced by monogastric animals



1 (Weiss and Leip 2012). The proportion of upstream/downstream emissions fall significantly for less-  
2 intensive and more-localised production systems (Mottet et al. 2017a).

3 *Transport and processing.* Recent globalisation of agriculture has promoted industrial agriculture and  
4 encouraged value-added processing and more distant transport of agricultural commodities, all  
5 leading to increased GHG emissions. Although greenhouse gas-intensive, food transportation plays an  
6 important role in food chains: it delivers food from producers to consumers at various distances,  
7 particularly to feed people in food-shortage zones from food-surplus zones. (See Section **Error!**  
8 **reference source not found.** for assessment of local food production.)

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

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

22

#### 23 **5.4.6 Greenhouse gas emissions associated with different diets**

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

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

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

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

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

19 However, Springmann et al. (2018a) found that there are locally applicable upper bounds to the  
20 footprint of diets around the world, and for lower-income countries undergoing a nutrition transition,  
21 adopting “Westernised” consumption patterns (over consumption, large amounts of livestock produce,  
22 sugar and fat), even if in culturally applicable local contexts, would increase emissions. The global  
23 mitigation potential of healthy but low-emissions diets is discussed in detail in Section **Error!**  
24 **reference source not found.**

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

30

## 31 **5.5 Mitigation options, challenges, and opportunities**

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

45 The AR5 ranked mitigation measures from simple mechanisms such as improved crop and livestock  
46 management (Smith et al. 2014) to more complex carbon dioxide reduction interventions, such as

1 afforestation, soil carbon storage and biomass energy projects with carbon capture and storage  
2 (BECCS). The AR5 WGIII AFOLU chapter (Smith et al. 2014) identified two primary categories of  
3 mitigation pathways from the food system:

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

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

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

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

23

### 24 **5.5.1 Supply-side mitigation options**

25 The IPCC AR5 identified options for GHG mitigation in agriculture including cropland management,  
26 restoration of organic soils, grazing land management and livestock, with a total mitigation potential  
27 of 1.5–4.0 GtCO<sub>2</sub>-eq yr<sup>-1</sup> by 2030 (compared to baseline emissions in the same year), at carbon prices  
28 from 20 to 100 USD/tCO<sub>2</sub>-eq (Smith et al. 2014). Reductions in GHG emissions intensity (emissions  
29 per unit product) from livestock and animal products can also be a means to achieve reductions in  
30 absolute emissions in specific contexts and with appropriate governance (*medium confidence*).  
31 Agroforestry mitigation practices include rotational woodlots, long-term fallow, and integrated land  
32 use.

33 Emissions from food systems can be reduced significantly by the implementation of practices that  
34 reduce carbon dioxide, methane, and nitrous oxide emissions from agricultural activities related to the  
35 production of crops, livestock, and aquaculture. These include implementation of more sustainable  
36 and efficient crop and livestock production practices aimed at reducing the amount of land needed per  
37 output (reductions in GHG emissions intensity from livestock and animal production can support  
38 reductions in absolute emissions if total production is constrained), bridging yield gaps, implementing  
39 better feeding practices for animals and fish in aquaculture, and better manure management (FAO  
40 2019a). Practices that promote soil improvements and carbon sequestration can also play an important  
41 role. In the South America region, reduction of deforestation, restoration of degraded pasture areas,  
42 and adoption of agroforestry and no-till agricultural techniques play a major role in the nation's  
43 voluntary commitments to reduce GHG emissions in the country's mitigation activities (Box 5.4).

44 The importance of supply-side mitigation options is that these can be directly applied by food system  
45 actors (farmers, processors, retailers, etc.) and can contribute to improved livelihoods and income  
46 generation. Recognising and empowering farming system actors with the right incentives and

1 governance systems will be crucial to increasing the adoption rates of effective mitigation practices  
2 and to build convincing cases for enabling GHG mitigation (Section 5.7 and Chapter 7).

#### 4 **Box 5.4 Towards sustainable intensification in South America region**

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

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

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

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

37 Engagement of the food industry and NGOs, particularly through the Soy Moratorium (from 2006)  
38 and Beef Moratorium (from 2009) also contributed effectively to keep deforestation at low historical  
39 rates in the regions where they were implemented (Nepstad et al. 2014; Gibbs et al. 2015). In 2012,  
40 Brazil also created the national land registry system (SICAR), a georeferenced database, which allows  
41 monitoring of farms' environmental liability in order to grant access to rural credit. Besides the

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<sup>2</sup> FOOTNOTE: The Legal Amazon is a Brazilian region of 501.6 Mha (ca. 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.

1 governmental schemes, funding agencies and the Amazon Fund provide financial resources to assist  
2 smallholder farmers to comply with environmental regulations (Jung et al. 2017).

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

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

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

24 Despite the reduced expansion rates into forest land, agricultural production continues to rise steadily  
25 in South America, relying on increasing productivity and substitution of extensive pastureland by  
26 crops. The average soybean and maize productivity in the region increased from 1.8 and 2.0 t ha<sup>-1</sup> in  
27 1990 to 3.0 and 5.0 t ha<sup>-1</sup>, respectively, in 2015 (FAOSTAT 2018). Yet, higher crop productivity was  
28 not enough to meet growing demand for cereals and oilseeds and cultivation continued to expand,  
29 mainly on grasslands (Richards 2015). The reconciliation of this expansion with higher demand for  
30 meat and dairy products was carried out through the intensification of livestock systems (Martha et al.  
31 2012). Nevertheless, direct and indirect deforestation still occurs, and recently deforestation rates have  
32 increased (INPE 2018), albeit they remain far smaller than observed in the 2000-2010 period.

33 The effort towards sustainable intensification has also been incorporated in agricultural policies. In  
34 Brazil, for instance, the reduction of deforestation, the restoration of degraded pasture areas, the  
35 adoption of integrated agroforestry systems<sup>3</sup> and no-till agricultural techniques play a major role in  
36 the nation's voluntary commitments to reduce GHG emissions in the country's NAMAs (Mozzer  
37 2011) and NDCs (Silva Oliveira et al. 2017; Rochedo et al. 2018). Such commitment under the  
38 UNFCCC is operationalised through the Low Carbon Agriculture Plan (ABC)<sup>4</sup>, which is based on low  
39 interest credit for investment in sustainable agricultural technologies (Mozzer 2011). Direct pasture  
40 restoration and integrated systems reduce area requirements (Strassburg et al. 2014), and increase  
41 organic matter (Gil et al. 2015; Bungenstab 2012; Maia et al. 2009), contributing to overall life cycle

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<sup>3</sup> FOOTNOTE: 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.

<sup>4</sup> FOOTNOTE: ABC - *Agricultura de Baixo Carbono* in Portuguese.

1 emissions reduction (Cardoso et al. 2016; de Oliveira Silva et al. 2016). Also, increased adoption of  
2 supplementation and feedlots, often based on agro-industrial co-products and agricultural crop  
3 residues are central to improve productivity and increase climate resilience of livestock systems  
4 (Mottet et al. 2017a; van Zanten et al. 2018).

5 Despite providing clear environmental and socio-economic co-benefits, including improved resource  
6 productivity, socio-environmental sustainability and higher economic competitiveness,  
7 implementation of the Brazilian Low Carbon Agriculture Plan is behind schedule (Köberle et al.  
8 2016). Structural inefficiencies related to the allocation and distribution of resources need to be  
9 addressed to put the plan on track to meet its emissions reduction targets. Monitoring and verification  
10 are fundamental tools to guarantee the successful implementation of the plan.

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

#### 19 20 **5.5.1.1 Greenhouse gas mitigation in croplands and soils**

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

30 New work since AR5 has focused on identifying pathways for the reductions of GHG emissions from  
31 agriculture to help meet Paris Agreement goals (Paustian et al. 2016; Wollenberg et al. 2016). Altieri  
32 and Nicholls (2017) have characterised mitigation potentials from traditional agriculture. Zomer et al.  
33 (2017) have updated previous estimates of global carbon sequestration potential in cropland soils.  
34 Mayer et al. (2018) converted soil carbon sequestration potential through agricultural land  
35 management into avoided temperature reductions. Fujisaki et al. (2018) identify drivers to increase  
36 soil organic carbon in tropical soils. For discussion of integrated practices such as sustainable  
37 intensification, conservation agriculture and agroecology, see Section 5.6.4.

38 Paustian et al. (2016) developed a decision-tree for facilitating implementation of mitigation practices  
39 on cropland and described the features of key practices. They observed that most individual mitigation  
40 practices will have a small effect per unit of land, and hence they need to be combined and applied at  
41 large scales for their impact to be significant. Examples included aggregation of cropland practices  
42 (e.g., organic amendments, improved crop rotations and nutrient management and reduced tillage) and  
43 grazing land practices (e.g., grazing management, nutrient and fire management and species  
44 introduction) that could increase net soil C stocks while reducing emissions of N<sub>2</sub>O and CH<sub>4</sub>.  
45 However, it is well-known that the portion of projected mitigation from soil C stock increase (about  
46 90% of the total technical potential) is impermanent, i.e., it would be effective for only 20–30 years  
47 due to saturation of the soil capacity to sequester carbon, whereas non-CO<sub>2</sub> emission reductions could

1 continue indefinitely. “Technical potential” is the maximum amount of GHG mitigation achievable  
2 through technology diffusion.

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

6

### 7 **5.5.1.2 Greenhouse gas mitigation in livestock systems**

8 The technical options for mitigating GHG emissions in the livestock sector have been the subject of  
9 recent reviews (Mottet et al., 2017b; Hristov et al. 2013a,b; Smithers 2015; Herrero et al. 2016a;  
10 Rivera-Ferre et al. 2016b) (Figure 5.11). They can be classified as either targeting reductions in  
11 enteric methane; reductions in nitrous oxide through manure management; sequestering carbon in  
12 pastures; implementation of best animal husbandry and management practices, which would have an  
13 effect on most GHG; and land use practices that also help sequester carbon. Excluding land use  
14 practices, these options have a technical mitigation potential ranging 0.2-2.4 GtCO<sub>2</sub>-eq yr<sup>-1</sup> (Herrero et  
15 al. 2016a; FAO 2007). See also Chapters 2 and 6 in this report.

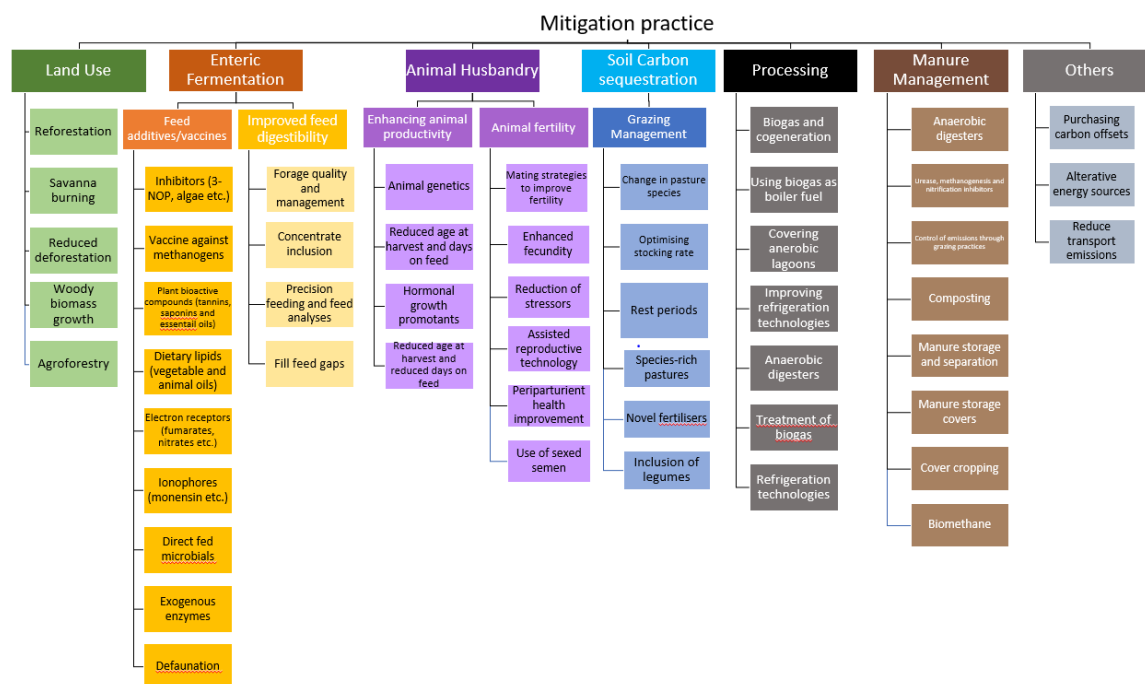
16 The opportunities for carbon sequestration in grasslands and rangelands may be significant (Conant  
17 2010), for instance, through changes in grazing intensity or manure recycling aimed at maintaining  
18 grassland productivity (Hirata et al. 2013). Recent studies have questioned the economic potential of  
19 such practices, i.e., whether they could implement at scale for economic gain (Garnett et al. 2017;  
20 Herrero et al. 2016a; Henderson et al. 2015). For instance, Henderson et al. (2015) found economic  
21 potentials below 200 MtCO<sub>2</sub>-eq yr<sup>-1</sup>. Carbon sequestration can occur in situations where grasslands  
22 are highly degraded (Garnett 2016). Carbon sequestration linked to livestock management could thus  
23 be considered as a co-benefit of well-managed grasslands, as well as a mitigation practice.

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

30 The implementation of strategies presented in **Error! Reference source not found.** builds on this  
31 differentiation, providing more depth compared to the previous AR5 analysis. Manure management  
32 strategies are more applicable in confined systems, where manure can be easily collected, such as in  
33 pigs and poultry systems or in smallholder mixed crop–livestock systems. More intensive systems,  
34 with strong market orientation, such as dairy in the US, can implement a range of sophisticated  
35 practices like feed additives and vaccines, while many market-oriented dairy systems in tropical  
36 regions can improve feed digestibility by improving forage quality and adding larger quantities of  
37 concentrate to the rations. Many of these strategies can be implemented as packages in different  
38 systems, thus maximising the synergies between different options (Mottet et al. 2017b).

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

42



2 **Figure 5.10 Technical supply-side mitigation practices in the livestock sector (adapted from Hristov et al.**  
 3 **2013b; Herrero et al. 2016b; Smith et al. 2014)**

#### 4 **5.5.1.3 Greenhouse gas mitigation in agroforestry**

5 Agroforestry can curb GHG emissions of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O in agricultural systems in both  
 6 developed and developing countries (See Glossary for definition) (see Chapter 2, Section 2.5.1 and  
 7 Figure 2.24). Soil carbon sequestration, together with biological N fixation, improved land health and  
 8 underlying ecosystem services may be enhanced through agricultural lands management practices  
 9 used by large-scale and smallholder farmers, such as incorporation of trees within farms or in hedges  
 10 (manure addition, green manures, cover crops, etc.), whilst promoting greater soil organic matter and  
 11 nutrients (and thus soil organic carbon) content and improve soil structure (Mbow et al. 2014b) (Table  
 12 5.5). The tree cover increases the microbial activity of the soil and increases the productivity of the  
 13 grass under cover. CO<sub>2</sub> emissions are furthermore lessened indirectly, through lower rates of erosion  
 14 due to better soil structure and more plant cover in diversified farming systems than in monocultures.  
 15 There is great potential for increasing above ground and soil C stocks, reducing soil erosion and  
 16 degradation, and mitigating GHG emissions.

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

21  
 22 **Table 5.5 Carbon sequestration potential for agroforestry (Mbow et al. 2014b)**

Source	Carbon sequestration (tCO <sub>2</sub> km <sup>-2</sup> yr <sup>-1</sup> ) (range)	C stock (tCO <sub>2</sub> km <sup>-2</sup> ) (range)	Max rotation period (years)
<b>Dominant parklands</b>	183 (73–293)	12,257 (2,091–25,983)	50
<b>Rotational woodlots<sup>a</sup></b>	1,431 (807–2,128)	6,789 (4,257–9,358)	5



<b>Tree planting-windrows-home gardens</b>	220.2 (146–293)	6,973 (-)	25
<b>Long term fallows, regrowth of woodlands in abandoned farms<sup>b</sup></b>	822 (80–2,128)	5,761 (-)	25
<b>Integrated land use</b>	1,145 (367–2,458)	28,589 (4,404–83,676)	50
<b>Soil carbon</b>	330 (91–587)	33,286 (4,771–110,100)	-

<sup>a</sup> May be classified as forestry on forest land, depending on the spatial and temporal characteristics of these activities.

<sup>b</sup> This is potentially not agro-forestry, but forestry following abandonment of agricultural land.

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 C sequestration potentials of differing agroforestry systems. These include sequestration rates in ranging from 954 (semi-arid); to 1,431 (temperate); 2,238 (sub-humid) and 3,670 tCO<sub>2</sub> km<sup>-2</sup> yr<sup>-1</sup> (humid). The global technical potential for agroforestry is 0.1–5.7 Gt CO<sub>2</sub>e yr<sup>-1</sup> (Griscom et al. 2017; Zomer et al. 2016; Dickie et al. 2014) (see Chapter 2, Section 2.5.1). Agroforestry-based carbon sequestration can be used to offset N<sub>2</sub>O and CO<sub>2</sub> 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 region (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 in 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.

*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

1 through anaerobic digestion) production (De Clercq et al. 2016) or for the production of microbial  
2 protein (Pikaar et al. 2018). Second-generation biorefineries, once the underlying technology is  
3 improved, may enable the generation of hydro-carbon from agricultural residues, grass, and woody  
4 biomass in ways that do not compete with food and can generate, along with biofuel, high-value  
5 products such as plastics (Nguyen et al. 2017). Second-generation energy biomass from residues may  
6 constitute a complementary income source for farmers that can increase their incentive to produce.  
7 Technologies include CHP (combined heat and power) or gas turbines, and fuel types such as bio-  
8 diesel, bio-pyrolysis (i.e., high temperature chemical transformation of organic material in the absence  
9 of oxygen), torrefaction of biomass, production of cellulosic bio-ethanol and of bio-alcohols produced  
10 by other means than fermentation, and the production of methane by anaerobic fermentation. (Nguyen  
11 et al. 2017).

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

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

26 Whilst these strategies may become very effective at reducing methane, they can be expensive and  
27 also impact on animal performance and/or welfare (Llonch et al. 2017). The use of novel fertilisers  
28 and/or plant species that secrete biological nitrification inhibitors also have the potential to  
29 significantly reduce N<sub>2</sub>O emissions from agricultural soils (Subbarao et al. 2009; Rose et al. 2018).

30 *Economic mitigation potentials of crop and livestock sectors.* Despite the large technical mitigation  
31 potential of the agriculture sector in terms of crop and livestock activities, its economic potential is  
32 relatively small in the short term (2030) and at modest carbon prices (less than USD 20 tC<sup>-1</sup>). For crop  
33 and soil management practices, it is estimated that 1.0–1.5 GtCO<sub>2</sub>-eq yr<sup>-1</sup> could be a feasible  
34 mitigation target at a carbon price of USD 20/tonne of carbon (Frank et al. 2018, 2017; Griscorn et al.  
35 2016; Smith et al. 2013; Wollenberg et al. 2016). For the livestock sector, these estimates range from  
36 0.12–0.25 GtCO<sub>2</sub>-eq yr<sup>-1</sup> at similar carbon prices (Herrero et al. 2016c; Henderson et al. 2017). But  
37 care is needed in comparing crop and livestock economic mitigation potentials due to differing  
38 assumptions.

39 Frank et al. (2018) recently estimated that the economic mitigation potential of non-CO<sub>2</sub> emissions  
40 from agriculture and livestock to 2030 could be up to four times higher than indicated in the AR5, if  
41 structural options such as switching livestock species from ruminants to monogastrics, or allowing for  
42 flexibility to relocate production to more efficient regions were implemented, at the same time as the  
43 technical options such as those described above. At higher carbon prices (i.e., at about USD 100tC<sup>-1</sup>),  
44 they found a mitigation potential of supply-side measures of 2.6 GtCO<sub>2</sub>-eq yr<sup>-1</sup>.

45 In this scenario, technical options would account for 38% of the abatement, while another 38% would  
46 be obtained through structural changes, and a further 24% would be obtained through shifts in  
47 consumption caused by food price increases. Key to the achievement of this mitigation potential lay in

1 the livestock sector, as reductions in livestock consumption, structural changes and implementation of  
2 technologies in the sector had some of the highest impacts. Regions with the highest mitigation  
3 potentials were Latin America, China and Sub-Saharan Africa. The large-scale implementability of  
4 such proposed sweeping changes in livestock types and production systems is likely very limited as  
5 well as constrained by long-established socio-economic, traditional and cultural habits, requiring  
6 significant incentives to generate change.

7 In summary, supply-side practices can contribute to climate change mitigation by reducing crop and  
8 livestock emissions, sequestering carbon in soils and biomass, and by decreasing emissions intensity  
9 within sustainable production systems (*high confidence*). The AR5 estimated the total economic  
10 mitigation potential of crop and livestock activities as 1.5–4.0 GtCO<sub>2</sub>-eq yr<sup>-1</sup> by 2030 at prices ranging  
11 from 20-100 USD/tCO<sub>2</sub>eq (*high confidence*). Options with large potential for GHG mitigation in  
12 cropping systems include soil carbon sequestration (at decreasing rates over time), reductions in N<sub>2</sub>O  
13 emissions from fertilisers, reductions in CH<sub>4</sub> emissions from paddy rice, and bridging of yield gaps.  
14 Options with large potential for mitigation in livestock systems include better grazing land  
15 management, with increased net primary production and soil carbon stocks, improved manure  
16 management, and higher-quality feed. Reductions in GHG emissions intensity (emissions per unit  
17 product) from livestock can support reductions in absolute emissions, provided appropriate  
18 governance structures to limit total production are implemented at the same time (*medium*  
19 *confidence*).

#### 21 **5.5.1.5 Greenhouse gas mitigation in aquaculture**

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

30 Proposed mitigation in aquaculture includes avoided deforestation. By halting annual mangrove  
31 deforestation in Indonesia, associated total emissions would be reduced 10-31% of estimated annual  
32 emissions from land use sector at present (Murdiyarso et al. 2015). Globally, 25% mangrove  
33 regeneration could sequester 0.54–0.65 millions tonnes carbon per year (Ahmed et al. 2017) of which  
34 0.17-0.21 could be through integrated or organic shrimp culture (Ahmed et al. 2018).

#### 36 **5.5.1.6 Cellular agriculture**

37 The technology for growing muscle tissue in culture from animal stem cells to produce meat, i.e.,  
38 “cultured” or “synthetic” or “in vitro” or “hydroponic” meat could in theory be constructed with  
39 different characteristics and be produced faster and more efficiently than traditional meat (Kadim et  
40 al. 2015). Cultured meat (CM) is part of so-called cellular agriculture, which includes production of  
41 milk, egg white and leather from industrial cell cultivation (Stephens et al. 2018). CM is produced  
42 from muscle cells extracted from living animals, isolation of adult skeletal muscle stem cells  
43 (myosatellite cells), placement in a culture medium which allow their differentiation into myoblasts  
44 and then, through another medium, generation of myocytes which coalesce into myotubes and grow  
45 into strands in a stirred-tank bioreactor (Mattick et al. 2015). Current technology enables the creation  
46 of beef hamburgers, nuggets, steak chips or similar products from meat of other animals, including  
47 wild species, although production currently is far from being economically feasible. Nonetheless, by

1 allowing bioengineering from the manipulation of the stem cells and nutritive culture, CM allows for  
2 reduction of harmful fatty acids, with advantages such as reduced GHG emissions, mostly indirectly  
3 through reduced land use (Bhat et al. 2015; Kumar et al. 2017b).

4 Tuomisto and de Mattos (2011) made optimistic technological assumptions, relying on cyanobacteria  
5 hydrolysate nutrient source, and produced the lowest estimates on energy and land use. Tuomisto and  
6 de Mattos (2011) conducted a lifecycle assessment that indicates that cultured meat could have less  
7 than 60% of energy use and 1% of land use of beef production and it would have lower GHG  
8 emissions than pork and poultry as well. Newer estimates (Alexander et al. 2017; Mattick et al. 2015)  
9 indicate a trade-off between industrial energy consumption and agricultural land requirements of  
10 conventional and cultured meat and possibly higher GWP than pork or poultry due to higher energy  
11 use. The change in proportion of CO<sub>2</sub> vs CH<sub>4</sub> could have important implications in climate change  
12 projections and, depending on decarbonisation of the energy sources and climate change targets,  
13 cultured meat may be even more detrimental than exclusive beef production (Lynch 2019).

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

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

## 27 **5.5.2 Demand-side mitigation options**

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

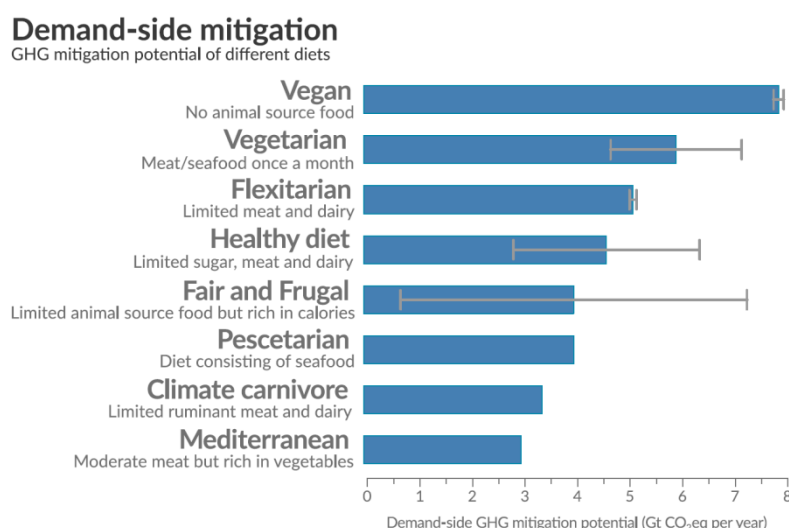
### 36 **5.5.2.1 Mitigation potential of different diets**

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

43 Figure 5.12 shows the technical mitigation potentials of some scenarios of alternative diets examined  
44 in the literature. Stehfest et al. (2009) were among the first to examine these questions. They found  
45 that under the most extreme scenario, where no animal products are consumed at all, adequate food  
46 production in 2050 could be achieved on less land than is currently used, allowing considerable forest

1 regeneration, and reducing land-based greenhouse gas emissions to one third of the reference  
 2 “business-as-usual” case for 2050, a reduction of 7.8 Gt CO<sub>2</sub>-eq yr<sup>-1</sup>. Springmann et al. (2016b)  
 3 recently estimated similar emissions reduction potential of 8 Gt CO<sub>2</sub>-eq yr<sup>-1</sup> from a vegan diet without  
 4 animal-sourced foods. This defines the upper bound of the technical mitigation potential of demand  
 5 side measures.

6 Herrero et al. (2016a) reviewed available options, with a specific focus on livestock products,  
 7 assessing technical mitigation potential across a range of scenarios, including “No animal products”,  
 8 “No meat”, “No ruminant meat”, and “Healthy diet” (reduced meat consumption). With regard to  
 9 ‘credible low-meat diets,’ where reduction in animal protein intake was compensated by higher intake  
 10 of pulses, emissions reductions by 2050 could be in the 4.3–6.4 Gt CO<sub>2</sub>-eq yr<sup>-1</sup>, compared to a  
 11 business-as-usual scenario. Of this technical potential, 1–2 GtCO<sub>2</sub>-eq yr<sup>-1</sup> come from reductions of  
 12 mostly non-CO<sub>2</sub> GHG within the farm gate, while the remainder was linked to carbon sequestration  
 13 on agricultural lands no longer needed for livestock production. When the transition to a low-meat  
 14 diet reduces the agricultural area required, land is abandoned and the re-growing vegetation can take  
 15 up carbon until a new equilibrium is reached. This is known as the land-sparing effect.



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

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

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

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

33 Flexitarian: 75% of meat and dairy replaced by cereals and pulses; at least 500 g per day fruits and vegetables;  
 34 at least 100 g per day of plant-based protein sources; modest amounts of animal-based proteins and limited  
 35 amounts of red meat (one portion per week), refined sugar (less than 5% of total energy), vegetable oils high in  
 36 saturated fat, and starchy foods with relatively high glycaemic index (Springmann et al. 2018; Hedenus et al.  
 37 2014)

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

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

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

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

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

1 Other studies have found similar results for potential mitigation linked to diets. For instance, Smith et  
2 al. (2013) analysed a dietary change scenario that assumed a convergence towards a global daily per-  
3 capita calorie intake of 2800 kcal cap<sup>-1</sup> day<sup>-1</sup> (11.7 MJ cap<sup>-1</sup> day<sup>-1</sup>), paired with a relatively low level of  
4 animal product supply, estimated technical mitigation potential in the range 0.7–7.3 Gt CO<sub>2</sub>-eq yr<sup>-1</sup> for  
5 additional variants including low or high-yielding bioenergy, 4.6 Gt CO<sub>2</sub>-eq yr<sup>-1</sup> if spare land is  
6 afforested.

7 Bajželj et al. (2014) developed different scenarios of farm systems change, waste management, and  
8 dietary change on GHG emissions coupled to land use. Their dietary scenarios were based on target  
9 kilocalorie consumption levels and reductions in animal product consumption. Their scenarios were  
10 “Healthy Diet”; Healthy Diet with 2500 kcal cap<sup>-1</sup> day<sup>-1</sup> in 2050; corresponded to technical mitigation  
11 potentials in the range 5.8 and 6.4 Gt CO<sub>2</sub>-eq yr<sup>-1</sup>.

12 Hedenus et al. (2014) explored further dietary variants based on the type of livestock product.  
13 “Climate Carnivore”, in which 75% of the baseline-consumption of ruminant meat and dairy was  
14 replaced by pork and poultry meat, and “Flexitarian”, in which 75% of the baseline-consumption of  
15 meat and dairy was replaced by pulses and cereal products. Their estimates of technical mitigation  
16 potentials by 2050 ranged 3.4– 5.2 Gt CO<sub>2</sub>-eq yr<sup>-1</sup>, the high end achieved under the Flexitarian.  
17 Finally, Tilman and Clark (2014) used stylised diets as variants that included “Pescetarian”,  
18 “Mediterranean”, “Vegetarian”, compared to a reference diet, and estimated technical mitigation  
19 potentials within the farm gate of 1.2–2.3 Gt CO<sub>2</sub>-eq yr<sup>-1</sup>, with additional mitigation from carbon  
20 sequestration on spared land ranging 1.8–2.4 Gt CO<sub>2</sub>-eq yr<sup>-1</sup>.

21 Studies have defined dietary mitigation potential as, for example, 20kg per person per week CO<sub>2</sub>-eq  
22 for Mediterranean diet, vs 13kg per person per week CO<sub>2</sub>-eq for vegan (Castañé and Antón 2017).  
23 Rosi et al. (2017) developed seven-day diets in Italy for about 150 people defined as omnivore 4.0 ±  
24 1.0; ovo-lacto-veggie 2.6 ± 0.6; and vegan 2.3 ± 0.5 kg CO<sub>2</sub>-eq per capita per day.

25 Importantly, many more studies that compute the economic and calorie costs of these scenarios are  
26 needed. Herrero et al. (2016a) estimated that once considerations of economic and calorie costs of  
27 their diet-based solutions were included, the technical range of 4.3–6.4 Gt CO<sub>2</sub>-eq yr<sup>-1</sup> in 2050 was  
28 reduced to 1.8–3.4 Gt CO<sub>2</sub>-eq yr<sup>-1</sup> when implementing a GHG tax ranging from 20–100 USD/tCO<sub>2</sub>.  
29 While caloric costs were low below 20 USD/tCO<sub>2</sub>, they ranged from 27–190 kcal cap<sup>-1</sup> day<sup>-1</sup> under  
30 the higher economic potential, thus indicating possible negative trade-offs with food security.

31 In summary, demand-side changes in food choices and consumption can help to achieve global GHG  
32 mitigation targets (*high confidence*). Low-carbon diets on average tend to be healthier and have  
33 smaller land footprints. By 2050, technical mitigation potential of dietary changes range from 2.7–6.4  
34 GtCO<sub>2</sub>-eq yr<sup>-1</sup> for assessed diets (*high confidence*). At the same time, the economic potential of such  
35 solutions is lower, ranging from 1.8–3.4 Gt CO<sub>2</sub>-eq yr<sup>-1</sup> at prices of 20–100 USD/tCO<sub>2</sub>, with caloric  
36 costs up to 190 kcal cap<sup>-1</sup> day<sup>-1</sup>. The feasibility of how to create economically viable transitions to  
37 more sustainable and healthy diets that also respect food security requirements needs to be addressed  
38 in future research.

39

#### 40 5.5.2.2 *Role of dietary preferences*

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

1 As suggested by Springmann et al. (2018a), per capita dietary emissions will translate into different  
2 realised diets, according to regional contexts including cultural and gendered norms (e.g. among some  
3 groups, eating meat is perceived as more masculine (Ruby and Heine 2011). In some cases, women  
4 and men have different preferences in terms of food, with women reporting eating healthier food  
5 (Imamura et al. 2015; Kiefer et al. 2005; Fagerli and Wandel 1999): these studies found that men tend  
6 to eat more meat, while women eat more vegetables, fruits and dairy products (Kanter and Caballero  
7 2012).

8 Food preferences can change over time, with the nutrition transition from traditional diets to high-  
9 meat, high-sugar, high-saturated fat diets being a clear example of significant changes occurring in a  
10 short period of time. Meat consumption per capita consistently responds to income with a saturating  
11 trend at high income levels (Sans and Combris 2015; Vranken et al. 2014). Some emerging economies  
12 have rapidly increased demand for beef, leading to pressure on natural resources (Bowles et al. 2019).  
13 In another example, by reducing beef consumption between 2005 and 2014, Americans avoided  
14 approximately 271 million metric tonnes of emissions (CO<sub>2</sub>eq) (NRDC 2017). See Section **Error!**  
15 **reference source not found.** for quantitative analysis. Attending farmers markets or buying directly  
16 from local producers has been shown to change worldviews (Kerton and Sinclair 2010), and food  
17 habits towards healthier diets (Pascucci et al. 2011) can be advanced through active learning (Milestad  
18 et al. 2010).

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

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

### 34 **5.5.2.3 Uncertainties in demand-side mitigation potential**

35 Both reducing ruminant meat consumption and increasing its efficiency are often identified as main  
36 options to reduce greenhouse gases emissions (GHGE) and to lessen pressure on land (Westhoek et al.  
37 2014) (See Section 5.6 for synergies and trade-offs with health and Section 5.7 for discussion of Just  
38 Transitions). However, analysing ruminant meat production is highly complex because of the extreme  
39 heterogeneity of production systems and due to the numerous products and services associated with  
40 ruminants (Gerber et al. 2015). See Supplementary Material Section SM5.5 for further discussion of  
41 uncertainties in estimates of livestock mitigation technical potential. Further, current market  
42 mechanisms are regarded as insufficient to decrease consumption or increase efficiency, and  
43 governmental intervention is often suggested to encourage mitigation in both the supply-side and  
44 demand-side of the food system (See Section 5.7) (Wirsenius et al. 2011; Henderson et al. 2018).

45 Minimising GHG emissions through mathematical programming with near-minimal acceptability  
46 constraints can be understood as a reference or technical potential for mitigation through diet shifts. In  
47 this context (Macdiarmid et al. 2012) found up to 36% reduction in emissions in UK with similar diet

1 costs applying fixed lifecycle analyses (LCA) carbon footprints (i.e., no rebound effects considered).  
2 Westhoek et al. (2014) found 25-40 % in emissions by halving meat, dairy and eggs intake in EU,  
3 applying standard IPCC fixed emission intensity factors. Uncertainty about the consequences of on-  
4 the-ground implementation of policies towards low ruminant meat consumption in the food system  
5 and their externalities remain noteworthy.

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

#### 16 **5.5.2.4 Insect-based diets**

17 Edible insects are, in general, rich in protein, fat, and energy and can be a significant source of  
18 vitamins and minerals (Rumpold and Schlüter 2015). Approximately 1,900 insect species are eaten  
19 worldwide, mainly in developing countries (van Huis 2013). The development of safe rearing and  
20 effective processing methods are mandatory for utilisation of insects in food and feed. Some insect  
21 species can be grown on organic side streams, reducing environmental contamination and  
22 transforming waste into high-protein feed. Insects are principally considered as meat substitutes, but  
23 worldwide meat substitute consumption is still very low, principally due to differences in food  
24 culture, and will require transition phases such as powdered forms (Megido et al. 2016; Smetana et al.  
25 2015). Wider consumer acceptability will relate to pricing, perceived environmental benefits, and the  
26 development of tasty insect-derived protein products (van Huis et al. 2015; van Huis 2013). Clearly  
27 increasing share of insect-derived protein has the potential to reduce GHG emissions otherwise  
28 associated with livestock production. No study to date however has quantified such potential.

#### 30 **5.5.2.5 Food loss and waste, food security, and land use**

31 Food loss and waste impacts food security by reducing global and local food availability, limiting  
32 food access due to increase in food price and decrease of producer income, and affecting future food  
33 production due to unsustainable use of natural resources (HLPE 2014). Food loss is defined as the  
34 reduction of edible food during production, postharvest, and processing, whereas food discarded by  
35 consumers is considered as food waste (FAO 2011b). Combined food loss and waste amount to a third  
36 of global food production (*high confidence*). During 2010-2016, global food loss and waste equalled  
37 8–10% of total GHG emissions (*medium confidence*); and cost about USD 1 trillion per year (FAO  
38 2014b) (*low confidence*).

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



1 In 2011, food loss and waste resulted in about 8–10% of the total anthropogenic greenhouse gas  
2 emissions of the entire food system. The mitigation potential of reduced food loss and waste from a  
3 full life-cycle perspective, i.e., considering both food supply chain activities and land use change, was  
4 estimated as 4.4 Gt CO<sub>2</sub>-eq yr<sup>-1</sup> (FAO 2015a, 2013b). At a global scale, loss and waste of milk,  
5 poultry meat, pig meat, sheep meat, and potatoes are associated with 3% of the global agricultural  
6 N<sub>2</sub>O emissions (more than 200 Gg N<sub>2</sub>O-N yr<sup>-1</sup> or 0.06 Gt CO<sub>2</sub>-eq yr<sup>-1</sup>) in 2009 (Reay et al. 2012). For  
7 the United States, 35% of energy use, 34% of blue water use, 34% of GHG emissions, 31% of land  
8 use, and 35% of fertiliser use related to an individual's food-related resource consumption were  
9 accounted for as food waste and loss in 2010 (Birney et al. 2017).

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

19 Avoiding food loss and waste will contribute to reducing emissions from the agriculture sector. By  
20 2050, agricultural GHG emissions associated with production of food that might be wasted may  
21 increase to 1.9–2.5 Gt CO<sub>2</sub>-eq yr<sup>-1</sup> (Hiç et al. 2016). When land use change for agriculture expansion  
22 is also considered, halving food loss and waste reduces the global need for cropland area by around  
23 14% and GHG emissions from agriculture and land use change by 22–28% (4.5 Gt CO<sub>2</sub>-eq yr<sup>-1</sup>)  
24 compared to the baseline scenarios by 2050 (Bajželj et al. 2014). The GHG emissions mitigation  
25 potential of food loss and waste reduction would further increase when life cycle analysis accounts for  
26 emissions throughout food loss and waste through all food system activities.

27 Reducing food loss and waste to zero might not be feasible. Therefore, appropriate options for the  
28 prevention and management of food waste can be deployed to reduce food loss and waste and to  
29 minimise its environmental consequences. Papargyropoulou et al. (2014) proposed the 3Rs (i.e.,  
30 reduction, recovery and recycle) options to prevent and manage food loss and waste. A wide range of  
31 approaches across the food supply chain is available to reduce food loss and waste, consisting of  
32 technical and non-technical solutions (Lipinski et al. 2013). However, technical solutions (e.g.,  
33 improved harvesting techniques, on-farm storage, infrastructure, packaging to keep food fresher for  
34 longer, etc.) include additional costs (Rosegrant et al. 2015) and may have impacts on local  
35 environments (FAO 2018b). Additionally, all parts of food supply chains need to become efficient to  
36 achieve the full reduction potential of food loss and waste (Lipinski et al. 2013).

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

45 In summary, reduction of food loss and waste can be considered as a climate change mitigation  
46 measure that provides synergies with food security and land use (*robust evidence, medium*  
47 *agreement*). Reducing food loss and waste reduces agricultural GHG emissions and the need for  
48 agricultural expansion for producing excess food. Technical options for reduction of food loss and

1 waste include improved harvesting techniques, on-farm storage, infrastructure, and packaging.  
2 However, the beneficial effects of reducing food loss and waste will vary between producers and  
3 consumers, and across regions. Causes of food loss (e.g., lack of refrigeration) and waste (e.g.,  
4 behaviour) differ substantially in developed and developing countries (*robust evidence, medium*  
5 *agreement*). Additionally, food loss and waste cannot be avoided completely.

6

#### 7 **5.5.2.6 Shortening supply chains**

8 Encouraging consumption of locally produced food and enhancing efficiency of food processing and  
9 transportation can in some cases minimise food loss, contribute to food security, and reduce GHG  
10 emissions associated with energy consumption and food loss. For example, Michalský and Hooda  
11 (2015), through a quantitative assessment of GHG emissions of selected fruits and vegetables in the  
12 UK, reported that increased local production offers considerable emissions savings. They also  
13 highlighted that when imports are necessary, importing from Europe instead of the Global South can  
14 contribute to considerable GHG emissions savings. Similar results were found by Audsley et al.  
15 (2010), with exceptions for some foods, such as tomatoes, peppers or sheep and goat meat. Similarly,  
16 a study in India shows that long and fragmented supply chains, which lead to disrupted price signals,  
17 unequal power relations perverse incentives and long transport time, could be a key barrier to  
18 reducing post-harvest losses (CIPHET 2007).

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

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

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

45

## 1       **5.6 Mitigation, Adaptation, Food Security, and Land Use – Synergies,** 2       **Trade-Offs, and Co-Benefits**

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

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

19      This section assesses the synergies and trade-offs for land-based atmospheric carbon dioxide removal  
20      measures, effects of mitigation measures on food prices, and links between dietary choices and human  
21      health. It then evaluates a range of integrated agricultural systems and practices that combine  
22      mitigation and adaptation measures, including the role of agricultural intensification. The roles of  
23      women’s empowerment and urban agriculture are examined, as well as interactions between SDG2  
24      (Zero Hunger) and SDG 13 (Climate Action).

25

## Food system response options

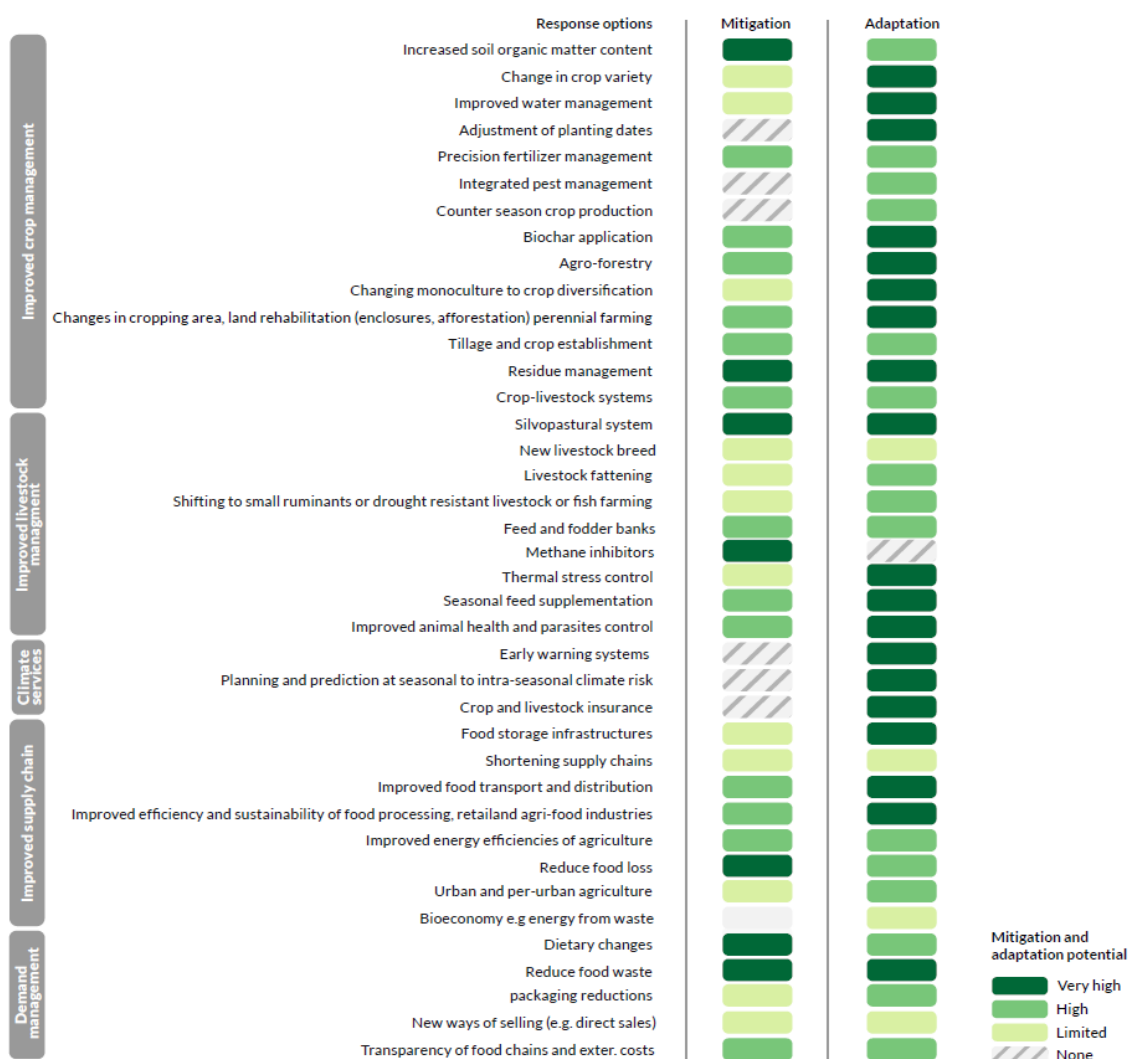


Figure 5.13 Response options related to food system and their potential impacts on mitigation and adaptation. Many response options offer significant potential for both mitigation and adaptation.

### 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; Rogelj et al. 2018, 2015, 2011). BECCS is not yet deployable at a commercial 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<sub>2</sub> 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

1 plant biomass. In BECCS, biomass carbon from plants is used in industrial processes (e.g., for  
2 electricity, hydrogen, ethanol, and biogas generation), releasing CO<sub>2</sub>, which is then captured and  
3 geologically stored (Greenberg et al. 2017; Minx et al. 2018).

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

7 Biochar is produced from controlled thermal decomposition of biomass in absence of oxygen  
8 (pyrolysis), a process that also yields combustible oil and combustible gas in different proportions.  
9 Biochar is a very stable carbon form, with storage on centennial timescales (Lehmann et al. 2006)  
10 (See also Chapter 4). Incorporated in soils, some authors suggest it may lead to improved water-  
11 holding capacity, nutrient retention, and microbial processes (Lehmann et al. 2015). There is  
12 however considerable uncertainty about the benefits and risks of this practice (The Royal Society  
13 2018).

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

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

32 Most land area available for CDR is currently pasture, estimated at 3,300 Mha globally (FAOSTAT  
33 2018). However, there is *low confidence* about how much low-productivity land is actually available  
34 for CDR (Lambin et al. 2013; Gibbs and Salmon 2015). There is also *low confidence* and *low*  
35 *agreement* if the transition to BECCS will take place directly on low-productivity grasslands  
36 (Johansson and Azar 2007), and uncertainty on the governance mechanisms required to avoid  
37 unwanted spill-over effects, for instance causing additional deforestation (Keles et al. 2018).

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

43 CDR-driven reductions in available pastureland area is a scenario of constant or increasing global  
44 animal protein output as proposed by (Searchinger et al. 2018). However, despite the recent reduction  
45 in meat consumption in western countries, this will require productivity improvements (Cohn et al.  
46 2014; Strassburg et al. 2014). It would also result in lower emission intensities and create conditions  
47 for increased soil carbon stocks (de Oliveira Silva et al. 2016; Searchinger et al. 2018; Soussana et al.

1 2019, 2013). At the same time, food security may be threatened if land-based mitigation displaced  
2 crops elsewhere, especially if to regions of lower productivity potential, higher climatic risk, and  
3 higher vulnerability.

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

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

20 There is *medium confidence* for the impact of CDR technologies on increased food prices and reduced  
21 food security, as these depend on several assumptions. Nevertheless, those impacts could be strong,  
22 with food prices doubling under certain scenario combinations (Popp et al. 2017). The impacts of  
23 land-mitigation policies on the reduction of dietary energy availability alone, i.e., without climate  
24 change impacts, is estimated at over 100 kcal.person<sup>-1</sup> day<sup>-1</sup> by 2050, with highest regional impacts in  
25 south Asia and sub-Saharan Africa (Hasegawa et al. 2018) (See Section 5.2). However, only limited  
26 pilot BECCS projects have been implemented to date (Lenzi et al. 2018). Integrated assessment  
27 models (IAMs) use theoretical data based on high-level studies and limited regional data from the few  
28 on-the-ground BECCS projects.

29 Furthermore, it has been suggested that several BECCS IAM scenarios rely on unrealistic  
30 assumptions regarding regional climate, soils and infrastructure suitability (Anderson and Peters  
31 2016), as well as international bioenergy trade (Lamers et al. 2011). Current global IAMs usually  
32 consider major trends in production potential and projected demand, overlooking major challenges for  
33 the development of a reliable international market. Such a market will have to be created from scratch  
34 and overcome a series of constraints, including trade barriers, logistics, and supply chains, as well as  
35 social, ecological and economic impacts (Matzenberger et al. 2015).

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

40

## 41 **5.6.2 Mitigation, food prices, and food security**

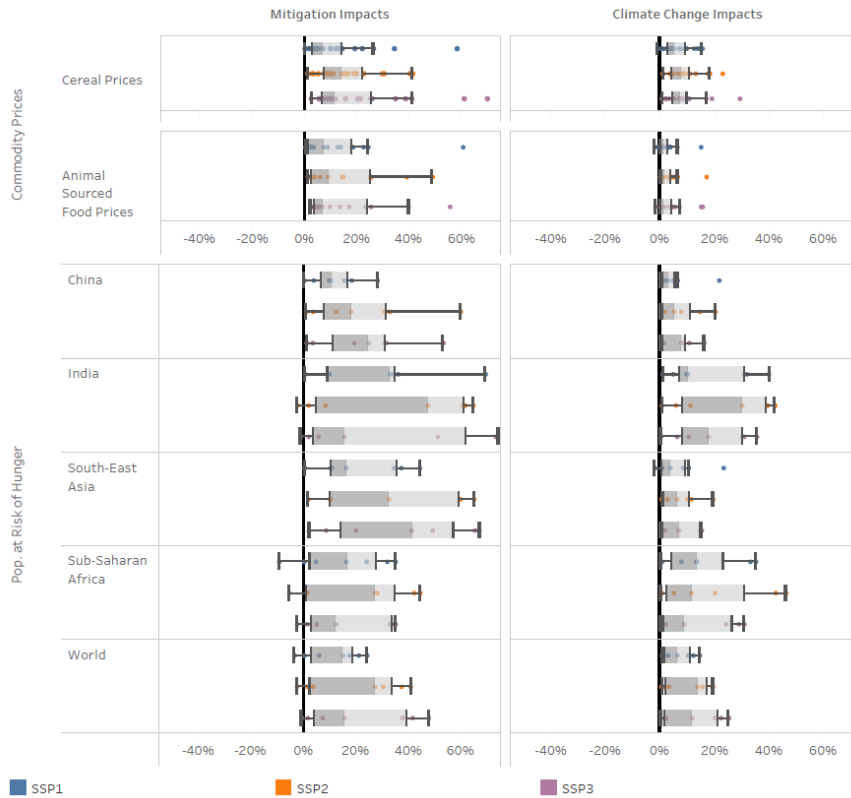
42 Food prices are the result of supply, demand and trade relations. Earlier studies (e.g., (Nelson et al.  
43 2009)) showed that recent climate impacts that reduced crop productivity led to higher prices and  
44 increased trade of commodities between regions, with asymmetric impacts on producers and  
45 consumers. In terms of published scenario analyses, the most affected regions tend to be Sub-Saharan  
46 Africa and parts of Asia, but there is significant heterogeneity in results between countries. Relocation

1 of production to less affected areas buffers these impacts to a certain extent, as well as potential for  
2 improvements in food production technologies (Hasegawa et al. 2018; van Meijl et al. 2017; Wiebe et  
3 al. 2015; Lotze-Campen et al. 2014; Valin et al. 2014; Robinson et al. 2014).

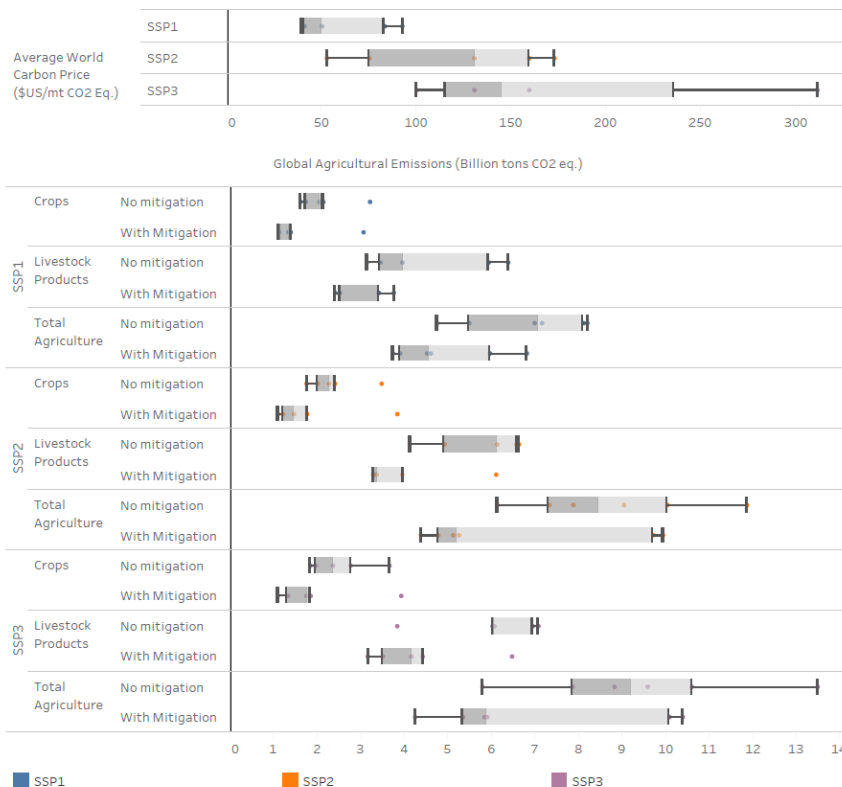
4 A newer, less studied impact of climate change on prices and their impacts on food security is the  
5 level of land-based mitigation necessary to stabilise global temperature. Hasegawa et al. (2018), using  
6 an ensemble of seven global economic models across a range of greenhouse gas emissions pathways  
7 and socioeconomic trajectories, suggested that the level of mitigation effort needed to reduce  
8 emissions can have a more significant impact on prices than the climate impacts themselves on  
9 reduced crop yields (Figure 5.14). This occurs because in the models, taxing GHG emissions leads to  
10 higher crop and livestock prices, while land-based mitigation leads to less land availability for food  
11 production, potentially lower food supply, and therefore food price increases.

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

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



1



2

3 **Figure 5.14 Regional impacts of climate change and mitigation on food price (top), population (pop) at**  
 4 **risk of hunger or undernourishment (middle), greenhouse gas emissions (bottom) in 2050 under different**  
 5 **socio-economic scenarios (SSP1, SSP2 and SSP3). Values indicate changes from no climate change and**  
 6 **no climate change mitigation scenario. MAGPIE, a global land use allocation model, is excluded due to**



1 **inelastic food demand. The value of India includes that of Other Asia in MAGNET, a global general**  
2 **equilibrium model (Hasegawa et al. 2018)**

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

8

### 9 **5.6.3 Environmental and health effects of adopting healthy and sustainable diets**

10 Two key questions arise from the potentially significant mitigation potential of dietary change: 1) Are  
11 ‘low-GHG emission diets’ likely to be beneficial for health? and 2) Would changing diets at scale  
12 provide substantial benefits? In short, what are the likely synergies and trade-offs between low-GHG  
13 emissions diets and food security, health, and climate change? See Supplementary Material Section  
14 SM5.6 for further discussion.

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

23 There are several studies that estimate health adequacy and sustainability and conclude that healthy  
24 sustainable diets are possible. These include global studies (e.g., (Willett et al. 2019; Swinburn et al.  
25 2019)), as well as localised studies (e.g., (Van Dooren et al. 2014). For example, halving  
26 consumption of meat, dairy products and eggs in the European Union would achieve a 40% reduction  
27 in ammonia emissions, 25–40% reduction in non-CO<sub>2</sub> GHG emissions (primarily from agriculture)  
28 and 23% per capita less use of cropland for food production, with dietary changes lowering health  
29 risks (Westhoek et al. 2014). In China, diets were designed that could meet dietary guidelines while  
30 creating significant reductions in GHG emissions (between 5% and 28%, depending on scenario)  
31 (Song et al. 2017). Changing diets can also reduce non-dietary related health issues caused by  
32 emissions of air pollutants; for example, specific changes in diets were assessed for their potential to  
33 mitigate PM<sub>2.5</sub> in China (Zhao et al. 2017b).

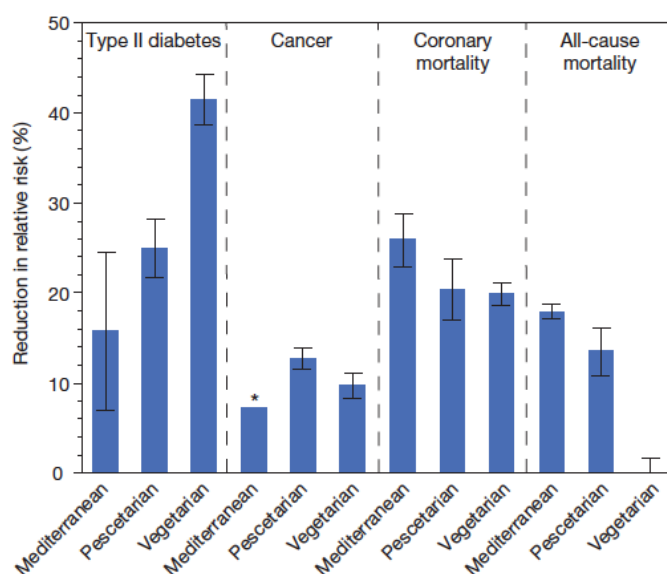
34 A range of studies are starting to estimate both health and environmental benefits from dietary shifts.  
35 For example, (Farchi et al. 2017) estimate health (colorectal cancer, cardio-vascular disease) and  
36 GHG reductions of “Mediterranean” diets, low in meat, in Italy, finding the potential to reduce deaths  
37 from colorectal cancer of 7-10% and CVD from 9-10%, and potential savings of up to 263 CO<sub>2</sub>-  
38 eq.person<sup>-1</sup>.yr<sup>-1</sup>. In the US, Hallström et al. (2017) found that adoption of healthier diets (consistent  
39 with dietary guidelines, and reducing amounts of red and processed meats) could reduce relative risk  
40 of coronary heart disease, colorectal cancer, and type 2 diabetes by 20–45%, US health care costs by  
41 USD 77–93 billion per year, and direct GHG emissions by 222–826 kg CO<sub>2</sub>-eq/capita yr<sup>-1</sup> (69–84 kg  
42 from the health care system, 153–742 kg from the food system). Broadly similar conclusions were  
43 found for the Netherlands (Biesbroek et al. 2014); and the UK (Friel et al. 2009; Milner et al. 2015).

44 Whilst for any given disease, there are a range of factors, including diet, that can affect it, and  
45 evidence is stronger for some diseases than others, a recent review found that an overall trend toward  
46 increased cancer risk was associated with unhealthy dietary patterns, suggesting that diet-related

1 choices could significantly affect the risk of cancer (Grosso et al. 2017). Tilman and Clark (2014)  
 2 found significant benefits in terms of reductions in relative risk of key diseases: type 2 diabetes,  
 3 cancer, coronary mortality and all causes of mortality (Figure 5.11).

### 5.6.3.1 Can dietary shifts provide significant benefits?

6 Many studies now indicate that dietary shifts can significantly reduce GHG emissions. For instance,  
 7 several studies highlight that if current dietary trends are maintained, this could lead to emissions  
 8 from agriculture of approximately 20 Gt CO<sub>2</sub>-eq yr<sup>-1</sup> by 2050, creating significant mitigation potential  
 9 (Pradhan et al. 2013b; Bajželj et al. 2014; Hedenus et al. 2014; Bryngelsson et al. 2017). Additionally  
 10 in the US, a shift in consumption towards a broadly healthier diet, combined with meeting the USDA  
 11 and Environmental Protection Agency's 2030 food loss and waste reduction goals, could increase *per*  
 12 *capita* food-related energy use by 12%, decrease blue water consumption by 4%, decrease green  
 13 water use by 23%, decrease GHG emissions from food production by 11%, decrease GHG emissions  
 14 from landfills by 20%, decrease land use by 32%, and increase fertiliser use by 12% (Birney et al.  
 15 2017). This study, however, does not account for all potential routes to emissions, ignoring, for  
 16 example, fertiliser use in feed production. Similar studies have been conducted, for China (Li et al.  
 17 2016), where adoption of healthier diets and technology improvements have the potential to reduce  
 18 food systems GHG emissions by >40% relative to those in 2010; and India (Green et al. 2017; Vetter  
 19 et al. 2017), where alternative diet scenarios can affect emissions from the food system by -20 to  
 20 +15%.



22  
 23 **Figure 5.11 Diet and health effects of different consumption scenarios (Tilman and Clark 2014) (\* reflects**  
 24 **data from a single study, hence no error bars)**

25 Springmann et al (2018a) modelled the role of technology, waste reduction and dietary change in  
 26 living within planetary boundaries (Rockström et al. 2009), with the climate change boundary being a  
 27 66% chance of limiting warming to less than 2°C. They found that all are necessary for achievement  
 28 of a sustainable food system. Their principal conclusion is that only by adopting a “flexitarian diet”,  
 29 as a global average, would climate change be limited to under two degrees. Their definition of a  
 30 flexitarian diet is fruits and vegetables, plant-based proteins, modest amounts of animal-based  
 31 proteins, and limited amounts of red meat, refined sugar, saturated fats, and starchy foods.

1 Healthy and sustainable diets address both health and environmental concerns (Springmann et al.  
2 2018b). There is high agreement that there are significant opportunities to achieve both objectives  
3 simultaneously. Contrasting results of marginal GHG emissions, i.e. variations in emissions as a result  
4 of variation in one or more dietary components, are found when comparing low to high emissions  
5 self-selected diets (diets freely chosen by consumers). (Vieux et al. 2013) found self-selected  
6 healthier diets with higher amounts of plant-based food products did not result in lower emissions,  
7 while (Rose et al. 2019) found that the lowest emission diets analysed were lower in meat but  
8 higher in oil, refined grains and added sugar. (Vieux et al. 2018) concluded that setting nutritional  
9 goals with no consideration for the environment may increase GHG emissions (GHGE).

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

16 Some studies have found a modest mitigation potential of diet shifts when economic and biophysical  
17 systems effects are taken into account in association with current dietary guidelines. Tukker et al.  
18 (2011), considering economic rebound effects of diet shifts (i.e., part of the gains would be lost due to  
19 increased use at lower prices), found maximum changes in emissions of the EU food system of 8%  
20 (less than 2% of total EU emissions) when reducing meat consumption by 40 to 58%. Using an  
21 economic optimisation model for studying carbon taxation in food but with adjustments of  
22 agricultural production systems and commodity markets in Europe (Zech and Schneider 2019) found  
23 a reduction of 0.41% in GHG emissions at a tax level of 50 USDt<sup>-1</sup>CO<sub>2</sub>eq. They estimate a leakage of  
24 43% of the greenhouse gas emissions reduced by domestic consumption, (i.e., although reducing  
25 emissions due to reducing consumption, around 43% of the emissions would not be reduced because  
26 part of the production would be directed to exports).

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

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

41

#### 42 **5.6.4 Sustainable integrated agricultural systems**

43 A range of integrated agricultural systems are being tested to evaluate synergies between mitigation  
44 and adaptation and lead to low-carbon and climate-resilient pathways for sustainable food security  
45 and ecosystem health (*robust evidence, medium agreement*). Integration refers to the use of practices  
46 that enhance an agroecosystem's mitigation, resilience, and sustainability functions. These systems  
47 follow holistic approaches with the objective of achieving biophysical, socio-cultural, and economic

1 benefits from land management systems (Sanz et al. 2017). These integrated systems may include  
2 agroecology (FAO et al. 2018; Altieri et al. 2015), climate smart agriculture (FAO 2011c; Lipper et  
3 al. 2014; Aggarwal et al. 2018), conservation agriculture (Aryal et al. 2016; Sapkota et al. 2015), and  
4 sustainable intensification (FAO 2011d; Godfray 2015), among others.

5 Many of these systems are complementary in some of their practices, although they tend to be based  
6 on different narratives (Wezel et al. 2015; Lampkin et al. 2015; Pimbert 2015). They have been tested  
7 in various production systems around the world (Dinesh et al. 2017; Jat et al. 2016; Sapkota et al.  
8 2015; Neufeldt et al. 2013). Many technical innovations, e.g., precision nutrient management  
9 (Sapkota et al. 2014) and precision water management (Jat et al. 2015), can lead to both adaptation  
10 and mitigation outcomes and even synergies; although negative adaptation and mitigation outcomes  
11 (i.e., trade-offs) are often overlooked. Adaptation potential of ecologically intensive systems includes  
12 crop diversification, maintaining local genetic diversity, animal integration, soil organic management,  
13 water conservation and harvesting the role of microbial assemblages (See Section 5.3). Technical  
14 innovations may encompass not only inputs reduction, but complete redesign of agricultural systems  
15 (Altieri et al. 2017) and how knowledge is generated (Levidow et al. 2014), including social and  
16 political transformations.

17

#### 18 **5.6.4.1 Agroecology**

19 Agroecology (see Glossary) (Francis et al. 2003; Gliessman and Engles 2014; Gliessman 2018),  
20 provides knowledge for their design and management, including social, economic, political, and  
21 cultural dimensions (Dumont et al. 2016). It started with a focus at the farm level but has expanded to  
22 include the range of food system activities (Benkeblia 2018). Agroecology builds systems resilience  
23 through knowledge-intensive practices relying on traditional farming systems and co-generation of  
24 new insights and information with stakeholders through participatory action research (Menéndez et al.  
25 2013). It provides a multidimensional view of food systems within ecosystems, building on  
26 indigenous and local knowledge (ILK) and co-evolving with the experiences of local people, available  
27 natural resources, access to these resources, and ability to share and pass on knowledge among  
28 communities and generations, emphasising the inter-relatedness of all agroecosystem components and  
29 the complex dynamics of ecological processes (Vandermeer 1995).

30 At the farm level, agroecological practices recycle biomass and regenerate soil biotic activities. They  
31 strive to attain balance in nutrient flows to secure favorable soil and plant growth conditions,  
32 minimise loss of water and nutrients, and improve use of solar radiation. Practices include efficient  
33 microclimate management, soil cover, appropriate planting time and genetic diversity. They seek to  
34 promote ecological processes and services such as nutrient cycling, balanced predator/prey  
35 interactions, competition, symbiosis, and successional changes. The overall goal is to benefit human  
36 and non-human communities in the ecological sphere, with fewer negative environmental or social  
37 impacts and fewer external inputs (Vandermeer et al. 1998; Altieri et al. 1998). From a food system  
38 focus, agroecology provides management options in terms of commercialisation and consumption  
39 through the promotion of short food chains and healthy diets (Pimbert and Lemke 2018; Loconto et al.  
40 2018).

41 Agroecology has been proposed as a key set of practices in building climate resilience (FAO et al.  
42 2018; Altieri et al. 2015). These can enhance on-farm diversity (of genes, species, and ecosystems)  
43 through a landscape approach (FAO 2018g). Outcomes include soil conservation and restoration and  
44 thus soil carbon sequestration, reduction of the use of mineral and chemical fertilisers, watershed  
45 protection, promotion of local food systems, waste reduction, and fair access to healthy food through  
46 nutritious and diversified diets (Pimbert and Lemke 2018; Kremen et al. 2012; Goh 2011; Gliessman  
47 and Engles 2014).

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

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

#### 13 **5.6.4.2 Climate-smart agriculture**

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

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

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

35 Mixed farming systems integrating crops, livestock, fisheries and agro-forestry could maintain crop  
36 yield in the face of climate change, help the system to adapt to climatic risk, and minimise GHG  
37 emissions by increasingly improving the nutrient flow in the system (Mbow et al. 2014a; Newaj et al.  
38 2016; Bioversity International 2016). Such systems can help diversify production and/or incomes and  
39 support efficient and timely use of inputs thus contributing to increased resilience, but require local  
40 seed and input systems and extension services. Recent whole farm modelling exercises have shown  
41 the economic and environmental (reduced GH emissions, reduced land use) benefits of integrated  
42 crop-livestock systems. Gil et al. (2018) compared different soy-livestock systems across multiple  
43 economic and environmental indicators, including climate resilience. However it is important to note  
44 that potential benefits are very context specific.

45 Although climate-smart agriculture involves a holistic approach, some argue that it narrowly focuses  
46 on technical aspects at the production level (Taylor 2018; Newell and Taylor 2018). Studying barriers  
47 to the adoption and diffusion of technological innovations for climate-smart agriculture in Europe,

1 Long et al. (2016) found that there was incompatibility between existing policies and climate-smart  
2 agriculture objectives, including barriers to the adoption of technological innovations.

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

12

### 13 **5.6.4.3 Conservation agriculture**

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

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

29 CA brings favourable changes in soil properties that affect the delivery of nature's contribution to  
30 people (NCPs) or ecosystem services including climate regulation through carbon sequestration and  
31 GHG emissions (Palm et al. 2013; Sapkota et al. 2017a). However, by analysing datasets for soil  
32 carbon in the tropics, Powlson et al. (2014, 2016) argued that the rate of SOC increase and resulting  
33 GHG mitigation in CA systems, from zero-tillage in particular, has been overstated (see also Chapter  
34 2).

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

44 CA adoption in Africa has been low despite more than three decades of implementation (Giller et al.  
45 2009), although there is promising uptake recently in east and southern Africa. This calls for a better  
46 understanding of the social and institutional aspects around CA adoption. Brown et al. (2017a) found

1 that institutional and community constraints hampered the use of financial, physical, human and  
2 informational resources to implement CA programs.

3 Gender is another variable to consider since at intra-household level, decision-making and benefits  
4 distribution. CA interventions have implications for labour requirements, labour allocation, and  
5 investment decisions, all of which impacting the roles of men and women (Farnworth et al. 2016) (see  
6 also Section 5.1.3). For example, in the global South, CA generally reduces labour and production  
7 costs and generally leads to increased returns to family labour (Aryal et al. 2015) although a gender  
8 shift of the labour burden to women have also been described (Giller et al. 2009).

9

#### 10 **5.6.4.4 Sustainable intensification**

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

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

32 Sustainable intensification acknowledges that enhanced productivity needs to be accompanied by  
33 maintenance of other ecosystem services and enhanced resilience to shocks (Vanlauwe et al. 2014). SI  
34 in intensively farmed areas may require a reduction in production in favour of increasing  
35 sustainability in the broad sense (Buckwell et al. 2014) (see Cross-Chapter Box 6: Agricultural  
36 Intensification). Hence, moving towards sustainability may imply lower yield growth rates than those  
37 maximally attainable in such situations. For areas that contain valuable natural ecosystems, such as  
38 the primary forest in the Congo basin, intensification of agriculture is one of the pillars of the strategy  
39 to conserve forest (Vanlauwe et al. 2014). Intensification in agriculture is recognised as one of the  
40 pathways to meet food security and climate change adaptation and mitigation goals (Sapkota et al.  
41 2017c).

42 However, SI does not always confer co-benefits in terms of food security and climate change  
43 adaption/mitigation. For example, in the case of Vietnam, intensified production of rice and pigs  
44 reduced GHG emissions in the short term through land sparing, but after two decades, the emissions  
45 associated with higher inputs were likely to outweigh the savings from land sparing (Thu Thuy et al.  
46 2009). Intensification needs to be sustainable in all components of food system by curbing agricultural

1 sprawl, rebuilding soils, restoring degraded lands, reducing agricultural pollution, increasing water  
2 use efficiency, and decreasing the use of external inputs (Cook et al, 2015).

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

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

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

24

## 25 **Cross-Chapter Box 6: Agricultural intensification: land sparing, land** 26 **sharing and sustainability**

27 Eamon Haughey (Ireland), Tim Benton (United Kingdom), Annette Cowie (Australia), Lennart  
28 Olsson (Sweden), Pete Smith (United Kingdom)

### 29 **Introduction**

30 The projected demand for more food, fuel and fibre for a growing human population necessitates  
31 intensification of current land use to avoid conversion of additional land to agriculture and potentially  
32 allow the sparing of land to provide other ecosystem services, including carbon sequestration,  
33 production of biomass for energy, and the protection of biodiversity (Benton et al. 2018; Garnett et al.  
34 2013). Land use intensity may be defined in terms of three components; (i) intensity of system inputs  
35 (land/soil, capital, labour, knowledge, nutrients and other chemicals), (ii) intensity of system outputs  
36 (yield per unit land area or per specific input) and (iii) the impacts of land use on ecosystem services  
37 such as changes in soil carbon or biodiversity (Erb et al. 2013). Intensified land use can lead to  
38 ecological damage as well as degradation of soil resulting in a loss of function which underpins many  
39 ecosystem services (Wilhelm and Smith 2018); (Smith et al. 2016). Therefore, there is a risk that  
40 increased agricultural intensification could deliver short-term production goals at the expense of  
41 future productive potential, jeopardising long term food security (Tilman et al. 2011).

42 Agroecosystems which maintain or improve the natural and human capital and services they provide  
43 may be defined as sustainable systems, while those which deplete these assets as unsustainable (Pretty  
44 and Bharucha 2014). Producing more food, fuel and fibre without the conversion of additional non-  
45 agricultural land while simultaneously reducing environmental impacts requires what has been termed



1 sustainable intensification (Godfray et al. 2010; FAO 2011e); see glossary and Cross-Chapter Box 6,  
2 Figure 1). Sustainable intensification (SI) may be achieved through a wide variety of means; from  
3 improved nutrient and water use efficiency via plant and animal breeding programs, to the  
4 implementation of integrated soil fertility and pest management practices, as well as by smarter land  
5 use allocation at a larger spatial scale: for example, matching land use to the context and specific  
6 capabilities of the land (Benton et al. 2018). However, implementation of SI is broader than simply  
7 increasing the technical efficiency of agriculture (“doing more with less”); it sometimes may require a  
8 reduction of yields to raise sustainability, and successful implementation can be dependent on place  
9 and scale. (Pretty et al. 2018), following (Hill 1985), highlights three elements to SI: (i) increasing  
10 efficiency, (ii) substitution of less beneficial or efficient practices for better ones, and (iii) system  
11 redesign to adopt new practices and farming systems (see Cross-Chapter Box 6, Table 1).

12 Under a land sparing strategy, intensification of land use in some areas, generating higher productivity  
13 per unit area of land, can allow other land to provide other ecosystem services such as increased  
14 carbon sequestration and the conservation of natural ecosystems and biodiversity (Balmford et al.  
15 2018; Strassburg et al. 2014). Conversely under a land sharing strategy less, or no, land is set aside,  
16 but lower levels of intensification are applied to agricultural land, providing a combination of  
17 provisioning and other functions such as biodiversity conservation from the same land (Green et al.  
18 2005). The two approaches are not mutually exclusive and the suitability of their application is  
19 generally system-, scale- and/or location specific (Fischer et al. 2014). One crucial issue for the  
20 success of a land sparing strategy is that spared land is protected from further conversion: as the  
21 profits from the intensively managed land increase, there is an incentive for conversion of additional  
22 land for production (Byerlee et al. 2014). Furthermore, it is implicit that there are limits to the SI of  
23 land at a local and also planetary boundary level (Rockström et al. 2009). These may relate to the  
24 “health” of soil, the presence of supporting services, such as pollination, local limits to water  
25 availability, or limits on air quality. This implies that it may not be possible to meet demand  
26 “sustainably” if demand exceeds local and global limits. There are no single global solutions to these  
27 challenges and specific in situ responses for different farming systems and locations are required.  
28 Bajželj et al. (2014) showed that implementation of SI, primarily through yield gap closure, had better  
29 environmental outcomes compared with business as usual trajectories. However, SI alone will not be  
30 able to deliver the necessary environmental outcomes from the food system – dietary change and  
31 reduced food waste are also required (Springmann et al. 2018a; Bajželj et al. 2014).

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

Approach	Sub-category	Examples/notes
<b>Improving efficiency</b>	Precision agriculture	High and low-technology options to optimise resource use.
	Genetic improvements	Improved resource use efficiency through crop or livestock breeding.
	Irrigation technology	Increase production in areas currently limited by precipitation (sustainable water supply required).
	Organisational scale-up	Increasing farm organisational scale (e.g. co-operative schemes) can increase efficiency via facilitation of mechanisation and precision techniques.
<b>Substitution</b>	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	Replacement 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.
<b>System redesign</b>	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

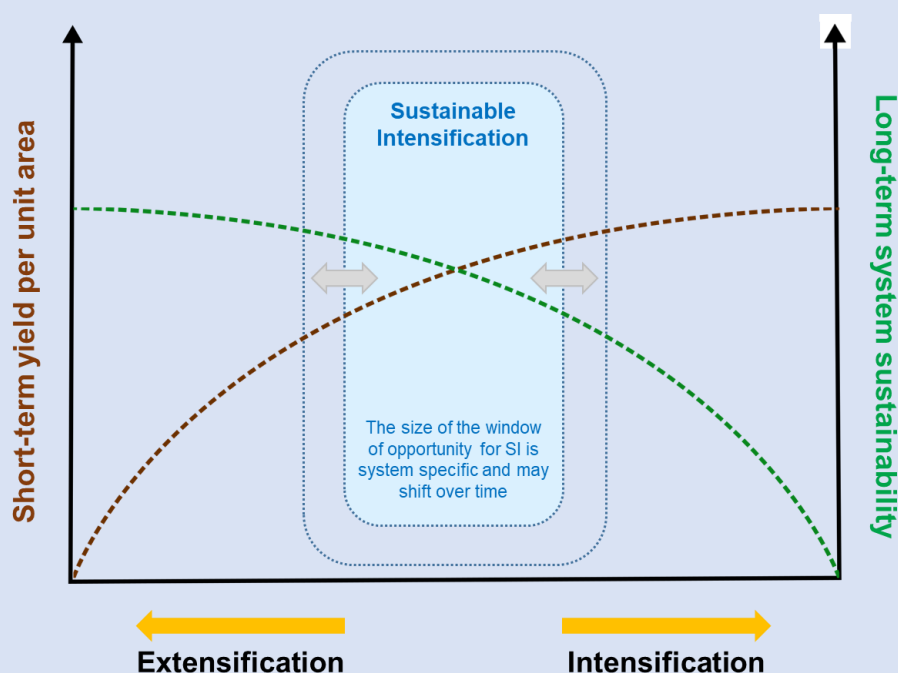
Precision farming usually refers to optimising production in fields through site-specific choices of crop varieties, agrochemical application, precise water management (e.g. in given areas or threshold moistures) and management of crops at a small scale (or livestock as individuals) (Hedley 2015). Precision 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 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 (Srbnovska 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).

### 1 *Low-tech precision agriculture*

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



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

### 21 **Sustainable intensification through farming system redesign**

22 SI requires equal weight to be placed on the sustainability and intensification components (Benton  
 23 2016; Garnett et al. 2013), Cross-Chapter Box 6, Figure 1 outlines the trade-offs which SI necessitates  
 24 between the intensity of land use against long-term sustainability. One approach to this challenge is  
 25 through farming system redesign including increased diversification.

### 26 *Diversification of intensively managed systems*

27 Incorporating higher levels of plant diversity in agroecosystems can improve the sustainability of  
 28 farming systems (Isbell et al. 2017). Where intensive land use has led to land degradation more  
 29 diverse land use systems such as intercropping can provide a more sustainable land use option with

1 co-benefits for food security, adaptation and mitigation objectives. For example, in temperate regions,  
2 highly productive agricultural grasslands used to produce meat and dairy products are characterised  
3 by monoculture pastures with high agrochemical inputs. Multi-species grasslands may provide a route  
4 to SI, as even a modest increase in species richness in intensively managed grasslands can result in  
5 higher forage yields without increased inputs, such as chemical fertiliser (Finn et al. 2013; Sanderson  
6 et al. 2013; Tilman et al. 2011). Recent evidence also indicates multispecies grasslands have greater  
7 resilience to drought, indicating co-benefits for adaptation (Hofer et al. 2016; Haughey et al. 2018).

#### 8 *Diversification of production systems*

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

#### 21 **Landscape Approaches**

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

#### 35 **Summary**

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

#### 44 **5.6.5 Role of urban agriculture**

45 Cities are an important actor in the food system in regard to both demand for food for urban dwellers  
46 and production of food in urban and peri-urban areas (see also cross-chapter box 4: Climate Change

1 and Urbanisation in Chapter 2). Both the demand side and supply side roles are important relative to  
2 climate change mitigation and adaptation strategies. Urban areas are home to more than half of the  
3 world's population, and a minimal proportion of the production; thus, they are important drivers for  
4 the development of the complex food systems in place today, in regard to supply chains and dietary  
5 preferences.

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

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

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

32 Urban and peri-urban agriculture is exposed to climate risks and urban growth that may undermine its  
33 long-term potential to address urban food security (Padgham et al. 2015). Therefore, there is a need to  
34 better understand the impact of urban sprawl on peri-urban agriculture; the contribution of urban and  
35 peri-urban agriculture to food self-sufficiency of cities; the risks posed by pollutants from urban areas  
36 to agriculture and vice-versa; the global and regional extent of urban agriculture; and the role that  
37 urban agriculture could play in climate resilience and abating malnutrition (Mok et al. 2014; Hamilton  
38 et al. 2014). Globally, urban sprawl is projected to consume 1.8–2.4% and 5% of the current  
39 cultivated land by 2030 and 2050 respectively, leading to crop calorie loss of 3–4% and 6–7%,  
40 respectively (Pradhan et al. 2014; Bren d'Amour et al. 2017). Kriewald et al. shows that the urban  
41 growth has the largest impacts in most of the sub-continent (e.g., Western, Middle, and Eastern  
42 Africa) while climate change will mostly reduce potential of urban and peri-urban agriculture in  
43 Southern Europe and Northern Africa.

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

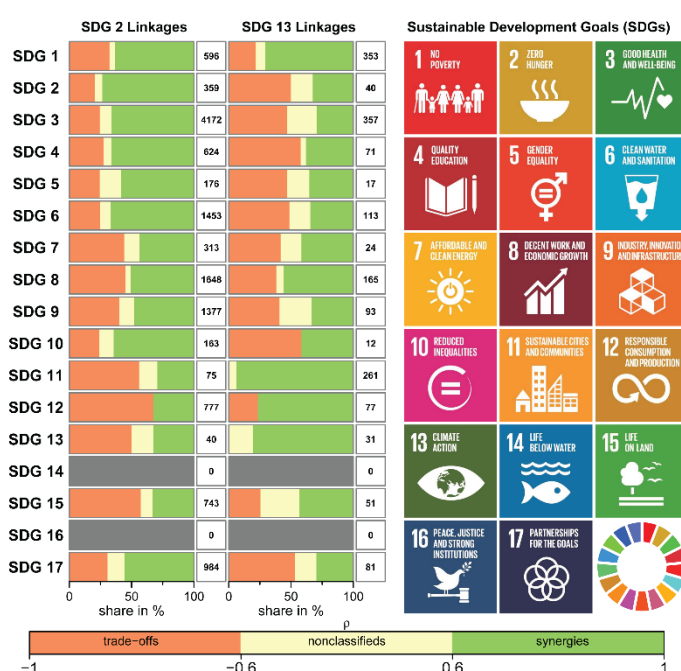
47



### 1 5.6.6 Links to the Sustainable Development Goals

2 In 2015, the Sustainable Development Goals (SDGs) and the Paris Agreement were two global major  
3 international policies adopted by all countries to guide the world to overall sustainability, within the  
4 2030 Sustainable Development Agenda and UNFCCC processes respectively. The 2030 Sustainable  
5 Development agenda includes 17 goals and 169 targets, including zero hunger, sustainable agriculture  
6 and climate action (United Nations 2015).

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



14

15 **Figure 5.16. Intra and inter-linkages for SDG 2 (Zero hunger) and SDG 13 (Climate action) at the global**  
16 **level using the official indicators of Sustainable Development Goals that consists data for 122 indicators**  
17 **for a total of 227 countries between the years 1983 and 2016 (United Nations Statistics Division 2016) and**  
18 **applying a statistical approach (Pradhan et al. 2017). Pradhan et al. (2017) defined synergy and trade-offs**  
19 **as significant positive ( $\rho > 0.6$ , red bar) and negative ( $\rho < -0.6$ , green bar) spearman correlation between**  
20 **SDG indicators, respectively. The  $\rho$  between 0.6 and -0.6 is considered as nonclassifieds (yellow bar). The**  
21 **correlation between unique pairs of indicator time-series is carried based on country data, e.g., between**  
22 **“prevalence of undernourishment” (an indicator for SDG 2.1) and “maternalmortality ratio” (an**  
23 **indicator for SDG 3.1). The data pairs can belong to the same goal or to two distinct goals. At the global**  
24 **level, intra-linkages of SDGs are quantified by the percentage of synergies, trade-offs, and nonclassifieds**  
25 **of indicator pairs belonging to the same SDG (here, SDG 2 and SDG 13) for all the countries. Similarly,**  
26 **SDG interlinkages are estimated by the percentage of synergies, trade-offs, and nonclassifieds between**  
27 **indicator pairs that fall into two distinct goals for all the countries. The grey bar shows insufficient data**  
28 **for analysis. The number of data pair used for the analysis is presented in the grey box.**

29 Ensuring food security (SDG 2) shows positive relations (synergies) with most goals (Pradhan et al.  
30 2017; International Council for Science (ICSU) 2017), but has trade-offs with SDG 12 (*Responsible*  
31 *Consumption and Production*) and SDG 15 (*Life on Land*) under current development paradigms

1 (Pradhan et al. 2017). Sustainable transformation of traditional consumption and production  
2 approaches can overcome these trade-offs based on several innovative methods (Shove et al. 2012).  
3 For example, sustainable intensification and reduction of food waste can minimise the observed  
4 negative relations between SDG 2 and other goals (Obersteiner et al. 2016) (see also Cross-Chapter  
5 Box 6 and Section 5.5.2). Achieving the target 12.3 of SDG 12 (Responsible Consumption and  
6 Production) “by 2030, to halve per capita global food waste at the retail and consumer levels and  
7 reduce food losses along production and supply chains, including post-harvest losses” will contribute  
8 to climate change mitigation.

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

16 Climate action (SDG 13) shows negative relations (trade-offs) with most goals and antagonistic to the  
17 2030 development agenda under the current development paradigm (Figure 5.16) (Lusseau and  
18 Mancini 2019; Pradhan 2019). The targets for SDG 13 have a high focus on climate change  
19 adaptation and the data for the SDG 13 indicators are limitedly available. SDG 13 shares two  
20 indicators with SDG 1 and SDG 11 (United Nations 2017) and therefore, has mainly positive linkages  
21 with these two goals. Trade-offs was observed between SDG 2 and SDG 13 for around 50% of the  
22 case (Pradhan et al. 2017).

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

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

## 34 **5.7 Enabling conditions and knowledge gaps**

35 To achieve mitigation and adaptation to climate change in food systems, enabling conditions are  
36 needed to scale up the adoption of effective strategies (such as those described in Sections 5.3 to 5.6  
37 and Chapter 6). These enabling conditions include multi-level governance and multi-sector  
38 institutions ( Supplementary Material Section SM5.7) and multiple policy pathways (Section 5.7.1,  
39 5.7.2). In this regard, the subnational level is gaining relevance both in food systems and climate  
40 change. Just Transitions are needed to address both climate change and food security (Section 5.7.3).  
41 Mobilisation of knowledge, education, and capacity will be required (Section 5.7.4) to fill knowledge  
42 gaps (Section 5.7.5).

43 Effective governance of food systems and climate change requires the establishment of institutions  
44 responsible for coordinating among multiple sectors (education, agriculture, environment, welfare,  
45 consumption, economic, health), levels (local, regional, national, global) and actors (governments,  
46 CSO, public sector, private sector, international bodies). Positive outcomes will be enegendered by

1 participation, learning, flexibility, and cooperation. See Supplementary Material Section SM5.7 for  
2 further discussion.

3

#### 4 **5.7.1 Enabling policy environments**

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

12

##### 13 **5.7.1.1 Agriculture and trade policy**

14 *Agriculture.* The thrust of agricultural policies over the last 50 years has been to increase productivity,  
15 even if at the expense of environmental sustainability (Benton and Bailey 2019). For example, in  
16 2007-9 46% of OECD support for agriculture was based on measures of output (price support or  
17 payments based on yields), 37% of support was based on the current or historical area planted, herd  
18 size (or correlated measures of the notional costs of farming), and 13% was payments linked to input  
19 prices. In a similar vein, non-OECD countries have promoted productivity growth for their  
20 agricultural sectors.

21 *Trade.* Along with agricultural policy to grow productivity, the development of frameworks to  
22 liberalise trade (such as the General Agreement on Tariffs and Trade (GATT) Uruguay Round, now  
23 incorporated into the World Trade Organisation) have been essential in stimulating the growth of a  
24 globalised food system. Almost every country has a reliance on trade to fulfil some or all of its local  
25 food needs, and trade networks have grown to be highly complex (Puma et al. 2015; MacDonald et al.  
26 2015; Fader et al. 2013; Ercsey-Ravasz et al. 2012). This is because many countries lack the capacity  
27 to produce sufficient food due to climatic conditions, soil quality, water constraints, and availability of  
28 farmland (FAO 2015b). In a world of liberalised trade, using comparative advantage to maximise  
29 production in high-yielding commodities, exporting excess production, and importing supplies of  
30 other goods supports economic growth.

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

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



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

5 Furthermore, Clapp (2016) showed that trade, often supported by high levels of subsidy support to  
 6 agriculture in some countries, can depress world prices and reduce incomes for other agricultural  
 7 exporters. Lower food prices that result from subsidy support may benefit urban consumers in  
 8 importing countries, but at the same time they may hurt farmers' incomes in those same countries. The  
 9 outmigration of smallholder farmers from the agriculture sector across the Global South is  
 10 significantly attributed to these trade patterns of cheap food imports (Wittman 2011; McMichael  
 11 2014; Akram-Lodhi and others 2013). Food production and trade cartels, as well as financial  
 12 speculation on food futures markets, affect low-income market-dependent populations.

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

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

24

### 25 **5.7.1.2 Scope for expanded policies**

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

33

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

Family	Sub-family	Scale	Interventions	Examples
<b>Supply-side efficiency</b>	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	Soils, nutrients, capital, labour (see

			projects	Cross-Chapter Box 6)
		N, R	Improving farmer training and knowledge sharing	Extension services, online access, field schools, farmer-to-farmer networks (CABI 2019)
	Land use planning	N, R, L	Land use planning for ecosystem services (remote sensing, indigenous and local knowledge)	Zoning, protected area networks, multifunctional landscapes, “land sparing” (see Cross-Chapter Box 6; Benton et al. 2018; Jones et al. 2013)
		N, R, L	Conservation agriculture programs	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)
<b>Raising profitability and quality</b>	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)
<b>Modifying demand</b>	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	I, N, L	Carbon pricing for selected food commodities	Food prices reflective of GHG gas emissions throughout production and

	n of carbon-intensive food			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 vs curative public health care 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)

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2 In summary, although agriculture is often thought to be shaped predominantly by agriculture and trade  
3 policies, there are over twenty families of policy areas that can shape agricultural production directly  
4 or indirectly (through environmental regulations or through markets, including by shaping consumer

1 behaviour). Thus, delivering outcomes promoting climate change adaptation and mitigation can arise  
2 from policies across many departments, if suitably designed and aligned.

### 3 4 **5.7.1.3 Health-related policies and cost savings**

5 The co-benefits arising from mitigating climate change through changing dietary patterns, and thus  
6 demand, have potentially important economic impacts (*high confidence*). The gross value added from  
7 agriculture to the global economy (GVA) was USD 1.9tn (in 2013 (FAO 2015c)), from a global  
8 agriculture economy (GDP) of USD 2.7tn (in 2016). In 2013, the FAO estimated an annual cost of  
9 USD 3.5tn for malnutrition (FAO 2013a).

10 However, this is likely to be an underestimate of the economic health costs of current food systems  
11 for several reasons: (1) Lack of data – for example there is little robust data in the UK on the  
12 prevalence of malnutrition in the general population (beyond estimates of obesity and surveys of  
13 malnourishment of patients in hospital and care homes, from which estimates over 3 million people in  
14 the UK are undernourished (BAPEN 2012)); (2) Lack of robust methodology to determine, for  
15 example, the exact relationship between overconsumption of poor diets, obesity and non-  
16 communicable diseases like diabetes, cardio-vascular disease, a range of cancers or Alzheimer's  
17 disease (Peditizi et al. 2016), (3) Unequal healthcare spending around the world.

18 In the US, the economic cost of diabetes, a disease strongly associated with obesity and affecting  
19 about 23 million Americans, is estimated at USD 327bn in 2017 (American Diabetes Association  
20 2018), with direct healthcare costs of USD 9,600 per person. By 2025, it is estimated that globally  
21 there will be over 700 million people with diabetes (NCD-RisC 2016b), over 30 times the number in  
22 the US. Even if a global average cost of diabetes per capita were a quarter of that in the US, the total  
23 economic cost of diabetes would be approximately the same as global agricultural GDP. Finally, (4)  
24 the role of agriculture in causing ill-health beyond dietary health, such as through degrading air  
25 quality (e.g., (Paulot and Jacob 2014)).

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

### 33 34 **5.7.1.4 Multiple policy pathways**

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

42 Obersteiner et al. (2016) show that increasing the average price of food is an important policy lever  
43 that, by reducing demand, reduces food waste, pressure on land and water, impacts on biodiversity  
44 and through reducing emissions, mitigates climate change and potentially helps to achieve multiple  
45 SDGs. Whilst such policy responses – such as a carbon tax applied to goods including food – has the  
46 potential to be regressive, affecting the poor differentially (Frank et al. 2017; Hasegawa et al. 2018;

1 Kehlbacher et al. 2016), and increasing food insecurity – further development of social safety nets can  
2 help to avoid the regressive nature (Hasegawa et al. 2018). Hasegawa et al. (2018) point out that such  
3 safety nets for vulnerable populations could be funded from the revenues arising from a carbon tax.

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

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

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

## 25 **5.7.2 Enablers for changing markets and trade**

26 “Demand” for food is not an exogenous variable to the food system but is shaped crucially by its  
27 ability to produce, market, and supply food of different types and prices. These market dynamics can  
28 be influenced by a variety of factors beyond consumer preferences (e.g., corporate power and  
29 marketing, transparency, the food environment more generally), and the ability to reshape the market  
30 can also depend on its internal resilience and/or external shocks (Challinor et al. 2018; Oliver et al.  
31 2018)).

### 33 **5.7.2.1 Capital markets**

34 Two areas are often discussed in regard to role of capital markets in shaping the food system. First,  
35 investment in disruptive technologies might stimulate climate-smart food systems (WEF/McKinsey &  
36 Company 2018; Bailey and Wellesley 2017), including alternative proteins, such as laboratory or  
37 “clean meat” (which has significant ability to impact on land use requirements) (Alexander et al.  
38 2017) (See Section 5.5.1.6). An innovation environment through which disruptive technology can  
39 emerge typically requires the support of public policy, whether in directly financing small and  
40 emerging enterprises, or funding research and development via reducing tax burdens.

41 Second, widespread adoption of (and perhaps underpinned by regulation for) natural capital  
42 accounting as well as financial accounting are needed. Investors can then be aware of the risk  
43 exposure of institutions, which can undermine sustainability through externalising costs onto the  
44 environment. The prime example of this in the realm of climate change is the Carbon Disclosure  
45 Project, with around 2500 companies voluntarily disclosing their carbon footprint, representing nearly  
46 60% of the world’s market capital (CDP 2018).

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### 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 can make an important contribution to resilience of the global food system (Lloyd 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; 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: Bioenergy and BECCS in mitigation scenarios, 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.

## 1 **5.7.4 Mobilising knowledge**

2 Addressing climate change-related challenges and ensuring food security requires all types of  
3 knowledge (formal/non-formal, scientific/indigenous, women, youth, technological). Miles et al.  
4 (2017) stated that a research and policy feedback that allows transitions to sustainable food systems  
5 must have at first a whole system approach. Currently, in transmitting knowledge for food security  
6 and land sustainability under climate change there are three major approaches: (1) public technology  
7 transfer with demonstration (extension agents); (2) public and private advisory services (for  
8 intensification techniques) and; (3) non-formal education with many different variants such as farmers  
9 field schools, rural resource centers; facilitation extension where front-line agents primarily work as  
10 “knowledge brokers” in facilitating the teaching–learning process among all types of farmers  
11 (including women and rural young people), or farmer-to-farmer, where farmers act themselves as  
12 knowledge transfer and sharing actors through peer processes.

13

### 14 **5.7.4.1 Indigenous and local knowledge**

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

29

### 30 **5.7.4.2 Citizen science**

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

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### 38 **5.7.4.3 Capacity building and education**

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

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

8 In developing countries, extension learning such as Farmer Field Schools – also known as Rural  
9 Resources Centers – are established to promote experiential learning on improved production and  
10 food transformation (FAO 2016c). While in developed countries, mass education campaigns are rising  
11 to reduce food waste, improved diets or acceptable food, and ultimately changes the structure of food  
12 industries that is based on the large-scale food products (Heller 2019; UNCCD 2017).

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

## 24 **5.7.5 Knowledge gaps and key research areas**

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

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

### 33 **5.7.5.1 Impacts and adaptation**

34 *Climate Services (Food availability).* Agriculture and food security is a priority area for the Global  
35 Framework for Climate Services (GFCS) a program of the World Meteorological Organization  
36 (WMO). The GFCS enables vulnerable sectors and populations to better manage climate variability  
37 and adapt to climate change (Hansen et al. 2018). Global precipitation datasets and remote sensing  
38 technologies can be used to detect local to regional anomalies in precipitation as a tool for devising  
39 early-warning systems for drought-related impacts, such as famine (Huntington et al. 2017). Crop  
40 model improvements are needed for evapotranspiration to guide crop water management in future  
41 climate (Cammarano et al. 2016).

42 *Crop and livestock genetics (Food availability, utilisation).* Advances in plant breeding are crucial for  
43 enhancing food security under changing climate for a wide variety of crops including fruits and  
44 vegetables as well as staples. Genetics improvement is needed in order to breed crops and livestock  
45 that can both reduce greenhouse gas emissions, increase drought and heat tolerance (e.g., rice), and  
46 enhance nutrition and food security (Nankishore and Farrell 2016; Kole et al. 2015). Many of these



1 characteristics already exist in traditional varieties, including orphan crops and autochthonous breeds,  
2 so research is needed to recuperate such varieties and evaluate their potential for adaptation and  
3 mitigation.

4 Phenomics-assisted breeding appears to be a promising tool for deciphering the stress responsiveness  
5 of crop and animal species (Papageorgiou 2017; Kole et al. 2015; Lopes et al. 2015; Boettcher et al.  
6 2015). Initially discovered in bacteria and archaea, CRISPR–Cas9 is an adaptive immune system  
7 found in prokaryotes and since 2013 has been used as a genome editing tool in plants. The main use  
8 of CRISPR systems is to achieve improved yield performance, biofortification, biotic and abiotic  
9 stress tolerance, with rice (*Oryza sativa*) being the most studied crop (Gao 2018; Ricoch et al. 2017).

10 *Climate impact models (Food availability)*. Understanding the full range of climate impacts on staple  
11 crops (especially those important in developing countries), fruits and vegetables is missing in the  
12 current climate impact models. Further, CO<sub>2</sub> effects on nutrition quality of different crops are just  
13 beginning to be parameterised in the models (Müller et al. 2014). Bridging these gap is essential for  
14 projecting future dietary diversity, healthy diets, and food security (Bisbis et al. 2018). Crop model  
15 improvements are needed for evapotranspiration to guide crop water management in future climate  
16 (Cammarano et al. 2016). Similarly, more studies are needed to understand the impacts of climate  
17 change on global rangelands and livestock and aquaculture, which have received comparatively less  
18 attention than the impacts on crop production.

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

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#### 25 **5.7.5.2 Emissions and mitigation**

26 *GHG emissions inventory techniques (Food utilisation)*. Knowledge gaps include food consumption-  
27 based emissions at national scales, embedded emissions (overseas footprints) of food systems,  
28 comparison of GHG emissions per type of food systems (e.g., smallholder and large-scale commercial  
29 food system), and GHG emissions from land-based aquaculture. An additional knowledge gap is the  
30 need for more socio-economic assessments of the potential of various integrated practices to deliver  
31 the mitigation potential estimated from a biophysical perspective. While studies often project how  
32 much CO<sub>2</sub> could theoretically be sequestered in soil, for instance, there is not yet discussion of the  
33 potential for this to be effectively monitored, verified, and implemented, once barriers and incentives  
34 to adoption of the techniques, practices, and technologies are considered. Thus, future research needs  
35 fill the gaps on evaluation of climate actions in the food system.

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

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

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### 2 **5.7.5.3 Synergies and trade-offs**

3 *Supply-side and demand-side mitigation and adaptation (Food availability, utilisation).* Knowledge  
4 gaps exist on potential and risk associated with novel mitigation technologies on supply side (e.g.,  
5 inhibitors, targeted breeding, cellular agriculture, etc.). Additionally, most integrated assessment  
6 models (IAMs) currently have limited regional data on BECCS projects because of little BECCS  
7 implementation (Lenzi et al. 2018). Hence, several BECCS scenarios seem to rely on unrealistic  
8 assumptions regarding regional climate, soils and infrastructure suitability (Köberle et al. 2019) as  
9 well as trade of international trade of bioenergy (Lamers et al. 2011).

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

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

24 *Food-Energy-Water Nexus (Food availability, utilisation, stability).* Emerging interdisciplinary  
25 science efforts are providing new understanding of the interdependence of food, energy, and water  
26 systems and these interdependencies are beginning to take into account climate change, food security,  
27 and AFOLU assessments (Scanlon et al. 2017; Liu et al. 2017). These science advances, in turn,  
28 provide critical information for coordinated management to improve the affordability, reliability, and  
29 environmental sustainability of food, energy, and water systems. Despite significant advances within  
30 the past decade, there are still many challenges for the scientific community. These include the need  
31 for interdisciplinary science related to the food-energy-water nexus; ground-based monitoring and  
32 modelling at local-to-regional scales (Van Gaalen et al. 2017); incorporating human and institutional  
33 behaviour in models; partnerships among universities, industry, and government to develop policy-  
34 relevant data; and systems modelling to evaluate trade-offs associated with food-energy-water  
35 decisions (Scanlon et al. 2017). However, the nexus approach, as a conceptual framework, requires  
36 the recognition that, although land and the goods and services it provides is finite, potential demand  
37 for the goods and services may be greater than the ability to supply them sustainably (Benton et al.  
38 2018). By addressing demand-side issues, as well as supply-side efficiencies, it provides a potential  
39 route for minimising trade-offs for different goods and services (Benton et al. 2018) and (Section 5.6).

40

## 41 **5.8 Future challenges to food security**

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

1

## 2 **5.8.1 Food price spikes**

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

14 Increasing extreme weather events can disrupt production and transport logistics. For example, in  
15 2012 the US Corn Belt suffered a widespread drought; US corn yield declined 16% compared to 2011  
16 and 25% compared to 2009. A record yield loss of 2016 in French that is attributed to a conjunction of  
17 abnormal warmth in late autumn and abnormal wet in the following spring (Ben-Ari et al. 2018) is  
18 another well-documented example. To the extent that such supply shocks are associated with climate  
19 change, they may become more frequent and contribute to greater instability in agricultural markets in  
20 the future. Furthermore, analogue conditions of past extremes might create significantly greater  
21 impacts in a warmer world. A study simulating analogous conditions to the Dustbowl drought in  
22 today's agriculture suggests that Dust-Bowl-type droughts today would have unprecedented  
23 consequences, with yield losses about 50% larger than the severe drought of 2012 (Glotter and Elliott  
24 2016). Damages at these extremes are highly sensitive to temperature, worsening by about 25% with  
25 each degree centigrade of warming. By mid-century, over 80% of summers are projected to have  
26 average temperatures that are likely to exceed the hottest summer in the Dustbowl years (1936)  
27 (Glotter and Elliott 2016).

28 How a shortfall in production – or an interruption in trade due to an event affecting a logistics choke-  
29 point (Wellesley et al. 2017) – of any given magnitude may create impacts depends on many  
30 interacting factors (Homer-Dixon et al. 2015; Tadasse et al. 2016; Challinor et al. 2018). The principal  
31 route is by affecting agricultural commodity markets, which respond to a perturbation through  
32 multiple routes as in Figure 5.17 **Error! Reference source not found.** This includes pressures from  
33 other sectors (such as if biofuels policy is incentivising crops for the production of ethanol, as  
34 happened in 2007–2008). The market response can be amplified by poor policies, setting up trade and  
35 non-trade barriers to exports, from countries seeking to ensure their local food security (Bailey et al.  
36 2015). Furthermore, the perception of problems can fuel panic buying on the markets that in turn  
37 drives up prices.

38 Thus, the impact of an extreme weather event on markets has both a *trigger* component (the event)  
39 and a *risk perception* component (Challinor et al. 2016, 2018). Through commodity markets, prices  
40 change across the world because almost every country depends, to a greater or lesser extent, on trade  
41 to fulfil local needs. Commodity prices can also affect local market prices by altering input prices,  
42 changing the cost of food aid, and through spill-over effects; for example, in 2007–2008 the grain  
43 affected by extreme weather was wheat, but there was a significant price spike in rice markets (Dawe  
44 2010).

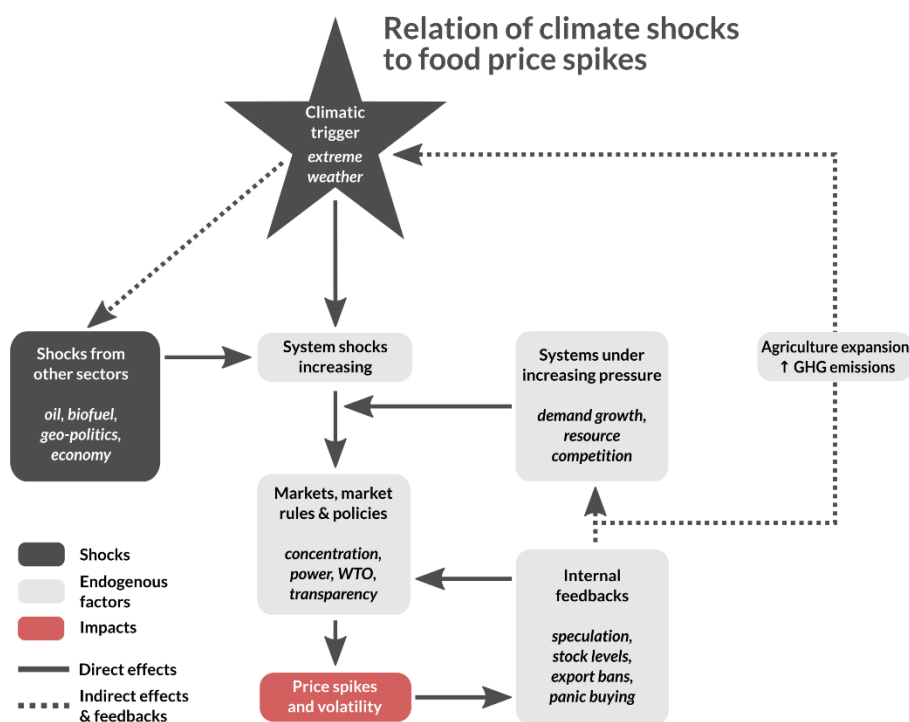
45 As discussed by Bailey et al. (2015), there are a range of adaptation measures that can be put in place  
46 to reduce the impact of climate-related production shortfalls. These include (a) ensuring transparency  
47 of public and private stocks, as well as improved seasonal forecasting to signal forthcoming yield

1 shortfalls (FAO 2016a; Ceglar et al. 2018; Iizumi et al. 2018), (b) building real or virtual  
 2 stockholdings, (c) increasing local productivity and diversity (as a hedge against a reliance on trade)  
 3 and (d) ensuring smoother market responses, through, for example, avoiding the imposition of export  
 4 bans.

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

10

11



12

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

### 15 **Box 5.5 Market drivers and the consequences of extreme weather in 2010-2011**

16 The 2010–2011 food price spike was initially triggered by the exceptional heat in summer 2010, with  
 17 an extent from Europe to the Ukraine and Western Russia (Barriopedro et al. 2011; Watanabe et al.  
 18 2013; Hoag 2014). The heatwave in Russia was extreme in both temperature (over 40°C) and duration  
 19 (from July to mid-August in 2010). This reduced wheat yields by approximately one third (Wegren  
 20 2011; Marchand et al. 2016). Simultaneously, in the Indus Valley in Pakistan, unprecedented rainfall  
 21 led to flooding, affecting the lives and livelihoods of 20 million people. There is evidence that these  
 22 effects were both linked and made more likely through climate change (Mann et al. 2017).

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

1 Analysis of responses to higher food prices in the developing world showed that lower-income groups  
2 responded by taking on more employment, reducing food intake, limiting expenditures, spending  
3 savings (if available), and participating in demonstrations. People often identified their problems as  
4 stemming from collusion between powerful incumbent interests (e.g., of politicians and big business)  
5 and disregard for the poor (Hossain and Green 2011). This politicised social response helped spark  
6 food-related civil protest, including riots, across a range of countries in 2010–2011 (Natalini et al.  
7 2017). In Pakistan, food price rises were exacerbated by the economic impacts of the floods, and  
8 which further contributed to food-related riots in 2010.

9 Price spikes also impact on food security in the developed world. In the UK, global commodity price  
10 inflation influenced local food prices, increasing food-price inflation by ~5 times at the end of 2010.  
11 Comparing household purchases over the five year period from 2007 to 2011 showed that the amount  
12 of food bought declined, on average, by 4.2%, whilst paying 12% more for it. The lowest income  
13 decile spent 17% more by 2011 than they did in 2007 (Holding et al. 2013; Tadasse et al. 2016).  
14 Consumers also saved money by trading down for cheaper alternatives. For the poorest, in the  
15 extreme situation, food became unaffordable: the Trussell Trust, a charity supplying emergency food  
16 handouts for people in crisis, noted a 50% increase in handouts in 2010.

## 18 **5.8.2 Migration and conflict**

19 Since the IPCC AR5 (Porter et al. 2014; Cramer et al. 2014), new work has advanced multi-factor  
20 methodological issues related to migration and conflict (e.g., Kelley et al. 2015, 2017; Werrell et al.  
21 2015; Challinor et al. 2018; Pasini et al. 2018). These in particular have addressed systemic risks to  
22 food security that result from cascading impacts triggered by droughts and floods and how these are  
23 related to a broad range of societal influences.

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

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

### 39 **5.8.2.1 Migration**

40 There has been a surge in international migration in recent years, with around five million people  
41 migrating permanently in 2016 (OECD 2017). Though the initial driver of migration may differ across  
42 populations, countries and contexts, migrants tend to seek the same fundamental objective: to provide  
43 security and adequate living conditions for their families and themselves. Food insecurity is a critical  
44 ‘push’ factor driving international migration, along with conflict, income inequality, and population

1 growth. The act of migration itself causes food insecurity, given the lack of income opportunities and  
2 adverse conditions compounded by conflict situations.

3 Warner et al. (2012) found the interrelationships between changing rainfall patterns, food and  
4 livelihood security in eight countries in Asia, Africa and Latin America. Several studies in Africa  
5 have found that persistent droughts and land degradation contributed to both seasonal and permanent  
6 migration (Gray 2011; Gray and Mueller 2012; Hummel 2015; Henry et al. 2004; Folami and Folami  
7 2013), worsening contextual vulnerability conditions of different households (Dasgupta et al. 2014).

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

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

22

### 23 **Box 5.6 Migration in the Pacific region: Impacts of climate change on food security**

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

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

40 Campbell (2014) describe the trends that lead to migration. First, climate change, including sea level  
41 rise, affect communities' land security, which is the physical presence on which to live and sustain  
42 livelihoods. Second, they impinge on livelihood security (especially food security) of island  
43 communities where the productivity of both subsistence and commercial food production systems is  
44 reduced. Third, the effects of climate change are especially severe on small-island environments since  
45 they result in declining ecological habitat. The effects on island systems are mostly manifested in  
46 atolls through erosion and inundation, and on human populations through migration. Population

1 growth and scenarios of climate change is *likely* to further induce food stress as impacts unfolds in  
2 coming decades (Campbell 2015).

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

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

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

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

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

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

43 Recurrences of natural disasters and crises threaten food security through impacts on traditional  
44 agriculture, causing the forced migration and displacement of coastal communities to highlands in  
45 search of better living conditions. Although considerable differences occur in the physical  
46 manifestations of severe storms, such climate stressors threaten the life-support systems of many atoll

1 communities (Campbell et al. 2014). Failure of these systems resulting from climate disasters propel  
2 vulnerable atoll communities into poverty traps, and low adaptive capacity could eventually force  
3 these communities to migrate.

#### 5 5.8.2.2 Conflict

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

15 Several studies have explored the causal links among climate change, drought, impacts on agricultural  
16 production, livelihoods, and civil unrest in Syria from 2007-2010, but without agreement as to the role  
17 played by climate in subsequent migration (Kelley et al. 2015, 2017; Challinor et al. 2018; Selby et al.  
18 2017; Hendrix 2018). Contributing factors that have been examined include rainfall deficits,  
19 population growth, agricultural policies, and influx of refugees that had placed burdens on the  
20 region's water resources (Kelley et al. 2015). Drought may have played a role as a trigger, as this  
21 drought was the longest and the most intense in the last 900 years (Cook et al. 2016; Mathbout et al.  
22 2018). Some studies linked the drought to widespread crop failure, but the climate hypothesis has  
23 been contested (Selby et al. 2017; Hendrix 2018). Recent evidence shows that the severe drought  
24 triggered agricultural collapse and displacement of rural farm families with approximately 300,000  
25 families going to Damascus, Aleppo and other cities (Kelley et al. 2017).

26 Persistent drought in Morocco during the early 1980s resulted in food riots and contributed to an  
27 economic collapse (El-Said and Harrigan 2014). A drought in Somalia that fuelled conflict through  
28 livestock price changes, establishing livestock markets as the primary channel of impact (Maystadt  
29 and Ecker 2014). Cattle raiding as a normal means of restocking during drought in the Great Horn of  
30 Africa led to conflict (ICPAC and WFP 2017) whereas a region-wide drought in northern Mali in  
31 2012 wiped out thousands of livestock and devastated the livelihoods of pastoralists, in turn swelling  
32 the ranks of armed rebel factions and forcing others to steal and loot for survival (Breisinger et al.  
33 2015).

34 On the other hand, inter-annual adjustments in international trade can play an important role in  
35 shifting supplies from food surplus regions to regions facing food deficits which emerge as a  
36 consequence of extreme weather events, civil strife, and/or other disruptions (Baldos and Hertel  
37 2015). A more freely functioning global trading system is tested for its ability to deliver improved  
38 long run food security in 2050.

39 In summary, given increasing extreme events and global and cross-sectoral interconnectedness, the  
40 food system is at increasing risk of disruption, e.g., via migration and conflict (*high confidence*).  
41 {5.2.3, 5.2.4}

## 43 Frequently Asked Questions

### 45 FAQ 5.1 How does climate change affect food security?



1 Climate change negatively affects all four pillars of food security: availability, access, utilisation and  
2 stability. Food availability may be reduced by negative climate change impacts on productivity of  
3 crops, livestock and fish, for instance due to increases in temperature and changes in rainfall patterns.  
4 Productivity is also negatively affected by increased pests and diseases, as well as changing  
5 distributions of pollinators under climate change. Food access and its stability may be affected  
6 through disruption of markets, prices, infrastructure, transport, manufacture, and retail, as well as  
7 direct and indirect changes in income and food purchasing power of low-income consumers. Food  
8 utilisation may be directly affected by climate change due to increases in mycotoxins in food and feed  
9 with rising temperatures and increased frequencies of extreme events, and indirectly through effects  
10 on health. Elevated atmospheric CO<sub>2</sub> concentrations can increase yields at lower temperature  
11 increases, but tend to decrease protein content in many crops, reducing their nutritional values.  
12 Extreme events, e.g., flooding, will affect the stability of food supply directly through disruption of  
13 transport and markets.

### 14 15 **FAQ 5.2 How can changing diets help address climate change?**

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

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